

# ANALYSIS OF RESIDENTIAL SOLAR SYSTEM



ELEC5206 Sustainable Energy Systems

GROUP 11

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# 1 Introduction

## 1.1 Description

The increasing use of fuel energy has produced countless harmful effects to the environment. The following reasons indeed enhance the necessity of adjusting the structure of power supply system by increasing the use of sustainable energy.

- Air pollution has raised concern globally
- Boosting increment in electricity bills
- Global warming issue raised by the use of fossil fuel

Solar power is considered to be unconstrained and eco-friendly. Solar power is also recognized as the latent renewable energy source[1]. The capacity of globally installed PV system has risen from 0.6GW to 136.7GW from 1995 to 2015 and the efficiency of PV system has been increased gradually [2].

To further investigate the feasibility of installing PV-battery system in residential building, specifically the case of working young couple, the aim to provide an optimized proposal by examining solar resource, tariff structure and designing the energy management system, hence determining the economic viability for the potential investor.

## 1.2 Objective

1. Locate a suitable residential house, including the geographical location of the house and parameters of the rooftop.
2. Determine the available PV output in the location. Matlab coding is used in this stage to calculate the PV power.
3. Estimate and calculate the demand power in the house. The demand is estimated every 30 minutes and the yearly demand is broken down into 12 situations
4. Investigate electricity price and tariff in Sydney
5. Design the PV/battery system including the brand and the price of PV panels, inverter and battery size.
6. Adjust the sample Matlab code to run for one year scale to determine the most economical way to use the battery.
7. Compare the prices with and without the PV/battery system to do the cash flow analysis as well as estimating how long it takes to cover the money spent on the system.

## 1.3 Team dynamics

In order to complete this project with high quality, every group member has injected best effort into this assignment. The group members show consistency and can communicate effectively. The specific tasks carried out by each member are listed in table.1.3.1, besides, the group members all contributed to the report.

Name	Task
Baoxiang Du	Solar resource, PV battery system design, energy management system design, cash flow analysis, matlab code
Shayan Wali	Location investigation, tariff analysis
Wenshuo Ma	PV Battery system design, cash flow analysis
Zhihao Yang	Electricity demand estimation, tariff analysis

Table1.3.1 Specific Task carried out by the group members

## 2 Determine the location of the building

### 2.1 House location:

The house is situated in  $33^{\circ} 53' 4.995''$  S,  $151^{\circ} 11' 6.4392''$  E. The satellite map of the building from Google map is illustrated in Fig. 2.1.1



Fig. 2.1.1 Satellite map of the building from Google map

The available area of the rooftop can be estimated by using Google maps. The collector will be placed on the North side of the roof which is the area in white and gray because the sun rises and sets passing East and West through the North in southern hemisphere. The length of rooftop area is about 8.1 meters and the wide is close to 6.93 meters. Furthermore, there is no trees or higher contractures around the location which will result in no shading possibility. However, the direction of house is not completely towards North, the facing direction of PV panels should be considered which means the collector should be 18 degree towards east. In results, it will completely face north and this will help it to collect the maximum isolation.

### 3 Determine the available solar resource at the chosen location

The solar resource available at the chosen location is the dominant factor to determine the number of solar panels to be installed. The solar insolation of year 2013 is investigated and the data are collected every half hour from the meteorological observatory. Although the latitude of the location provides an overview of the solar insolation, the solar insolation on the PV panel is also influenced by air temperature and cloud coverage.

#### 3.1 Solar altitude

The altitude of the sun at solar noon in the year varies in different season. In each day, the altitude of the sun is highest at solar noon. As shown in Fig.3.1.1, the solar declination varies between  $\pm 23.45^\circ$  and is modelled by a sinusoidal equation (n represents the number of the day) [3]:

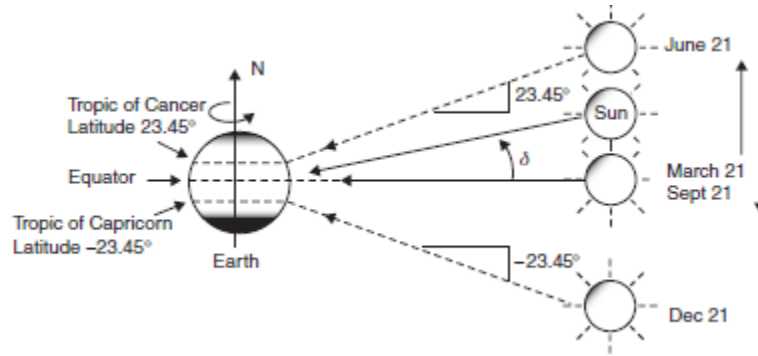


Fig3.1.1 An alternative view of solar declination angle

$$\delta = 23.45 * \sin\left(\frac{360}{365}(n - 81)\right)$$

At any time other than solar noon, the solar hour angle, solar altitude and solar azimuth angle are given as below:

Solar hour angle:  $H = \frac{15}{h}(\text{hour before solar noon})$

Solar altitude angle:

$$\beta = 180 - \arcsin(\cos L \cos \delta \cos H + \sin L \sin \delta) (L \text{ represents Latitude})$$

Solar azimuth angle:

$$\phi_s = -\arcsin\left(\frac{\cos \delta \cos H}{\cos \beta}\right)$$

If  $\cos H \geq \frac{\tan \delta}{\tan L}$  then  $|\phi_s| \leq 90^\circ$ , otherwise  $|\phi_s| > 90^\circ$

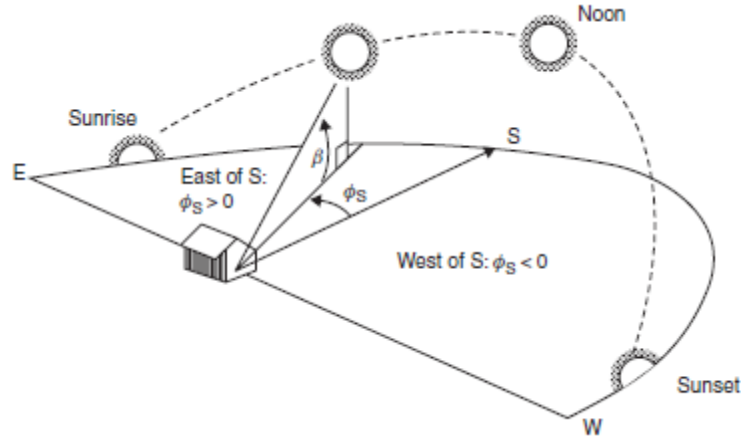


Fig.3.1.2 Altitude angle and azimuth angle of the sun

## 3.2 Clear sky insolation

The insolation on a given solar panel is composed of three parts:

- Direct beam radiation
- Diffuse radiation
- Reflected radiation

In this project, the theoretical value of the radiation calculated from the following formula are used to determine the PV output of the system while the average solar radiation provided by PVEducation is used as a reference to determine the accuracy.

### 3.2.1 Direct Beam radiation

Direct-beam radiation, the radiation generated by a straight line through atmosphere to the receiving PV panel, is determine by the apparent extraterrestrial flux  $A$ , Optical depth  $k$  and air mass ratio  $m$  [4].

$$I_B = A * e^{-km}$$

$$A = 1160 + 75\sin\left[\frac{360}{365}(n - 275)\right]$$

$$k = 0.174 + 0.035\sin\left[\frac{360}{365}(n - 100)\right]$$

$$m = \sqrt{(708\sin\beta)^2 + 1417} - 708\sin\beta$$

However, direct beam radiation is also influenced by incidence angle formed between the normal of the solar surface and the incoming beam radiation:

$$I_{BC} = I_B \cos\theta$$

$\cos\theta = \cos\beta \cos(\phi_s - \phi_c) \sin\Sigma + \sin\beta \cos\Sigma$  where  $\Sigma$  is the tilting angle of the solar panel

In this project, since the roof facing north has enough room to allocate the PV panel, the PV panel are placed directly facing the north in which  $\phi_c = 0$  hence the solar insolation is maximized which is shown in Fig.3.2.1.1.

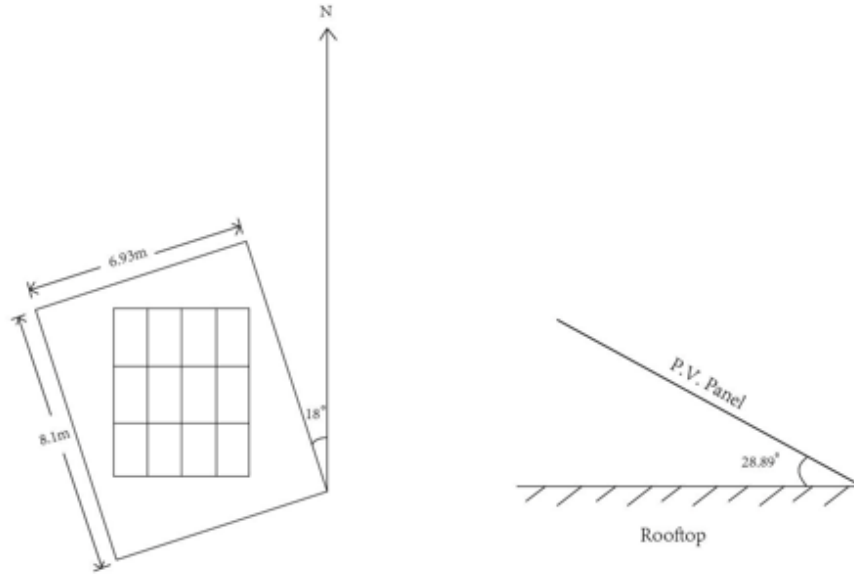


Fig.3.2.1.1 Layout and tilting angle of solar panel

### 3.2.2 Diffuse radiation and reflected radiation

The diffuse and reflected insolation are both affected by the sky diffuse factor  $C$ , reflected radiation is also related with the reflectance  $\rho$

$$C = 0.095 + 0.04 * \sin\left(\frac{360}{365}(n - 100)\right)$$

$$I_{DC} = I_{DH} \left[ \frac{1 + \cos\Sigma}{2} \right] = I_B C \left[ \frac{1 + \cos\Sigma}{2} \right]$$

$$I_{RC} = \rho I_H \left[ \frac{1 - \cos\Sigma}{2} \right] = I_B \rho (C + \sin\beta) \left[ \frac{1 - \cos\Sigma}{2} \right]$$

The total insolation can be estimated by combining the direct beam radiation, diffuse radiation and reflected radiation.

$$I_{total} = I_{BC} + I_{DC} + I_{RC}$$

## 3.3 Tracking system

### 3.3.1 Fixed tilting angle

In the previous discussion, the solar insolation of a fixed angle is discussed. In this project, the tilting angle of the PV panel is optimised according to the latitude of the location ( $-33.9455^\circ$ ).

$\Sigma = 0.76 * L - 3.1^\circ$  [5], since the building is located in south hemisphere.

### 3.3.2 Single Axis Tracking

One of the common tracking configuration, Horizontal North-South (HNS) tracking system is examined as a case in the simulation. The effective incidence angle and corresponding radiations of HNS tracking system are given by:

$$\cos\theta = \sqrt{1 - (\cos\beta\cos\phi_s)^2}$$

$$I_{BC} = I_B \cos\theta$$

$$I_{DC} = I_{DH} \left[ \frac{1 + (\sin\beta/\cos\theta)}{2} \right] = I_B C \left[ \frac{1 + (\sin\beta/\cos\theta)}{2} \right]$$

$$I_{RC} = \rho I_H \left[ \frac{1 - (\sin\beta/\cos\theta)}{2} \right] = I_B \rho (C + \sin\beta) \left[ \frac{1 - (\sin\beta/\cos\theta)}{2} \right]$$

### 3.3.3 Two Axis Tracking

Two axis tracking system can ensure the sun is always directly radiating the solar panel. Hence the incidence angle  $\theta = 0^\circ$ .

$$I_{BC} = I_B$$

$$I_{DC} = I_{DH} \left[ \frac{1 + \sin\beta}{2} \right] = I_B C \left[ \frac{1 + \sin\beta}{2} \right]$$

$$I_{RC} = \rho I_H \left[ \frac{1 - \sin\beta}{2} \right] = I_B \rho (C + \sin\beta) \left[ \frac{1 - \sin\beta}{2} \right]$$

## 3.4 Influence of cloud coverage

To quantitatively analyze the effect of cloud coverage, a formula representing the relationship between solar insolation and cloud coverage is formed based on ten years continuous data collected from Meteorological Observatory Hamburg. The amount of cloud is divided into 8 levels. Taking the solar insolation at clear sky as reference, solar insolation with different amount of cloud is given by

$$\frac{I(N)}{I(0)} = 1 - 0.75(N/8)^{3.4} \text{ [6]}$$

To estimate the cloud amount of the chosen location, the data is chosen from the nearest meteorological observatory 66037 Sydney Airport AMO ( $L = -33.9465^\circ$ ), three sets of cloud amount are given in the data, in which the first group of data is used according to completeness. A new set of data is then re-organized only containing a whole year complete data of temperature and cloud amount. The solar insolation for a year taking into consideration of cloud coverage is

then generated. The result is compared with peak sun hours from PVEducation and the data is modified due to discrepancy. The discrepancy comes from the accuracy of the cloud coverage of group 1 and the formula given above is based on the data from 1964 to 1973. The climate has been changed greatly since then. The formula is then modified to fit the curve of peak sun hours.

$$\frac{I(N)}{I(0)} = \left(1 - 0.75 \left(\frac{N}{8}\right)^{3.4}\right) * 0.7$$

## 3.5 Photovoltaic System

### 3.5.1 Impact of Temperature

The temperature of the solar cell increases as the solar irradiance received by the panel increases, which can harm the performance of the solar panel. The nominal Operating Cell Temperature is provided by the manufacture. The temperature of the solar panel is given by:

$$T_{cell} = T_{amb} + \frac{NOCT - 20C^{\circ}}{0.8} \times S [7]$$

The efficiency of the solar panel drops as the temperature increases. According to the area of the solar panel and the solar irradiance received at each point, the output power is given by:

$$P_{TEMP} = S * A * \eta * (1 - 0.0045 \times (T_{cell} - 25))$$

### 3.5.2 Other losses

Other losses in the PV system can be raised by the accumulation of the dirt on the surface of the solar panel, which is typically 3% [8]. In order to avoid shading effect, the PV system is equipped with bypass diode, which typically allow the diode drop of about 0.6V to occur. Bypass diode significantly reduces shading effect. The combined loss of bypass diode and mismatched modules is estimated as 3% [9].

## 3.6 Result analysis and adjustment

### 3.6.1 Daily insolation analysis

The data with half-hourly resolution is analyzed by plotting the instantaneous solar insolation of different configurations on a typical day, over a week and daily solar insolation over a year.

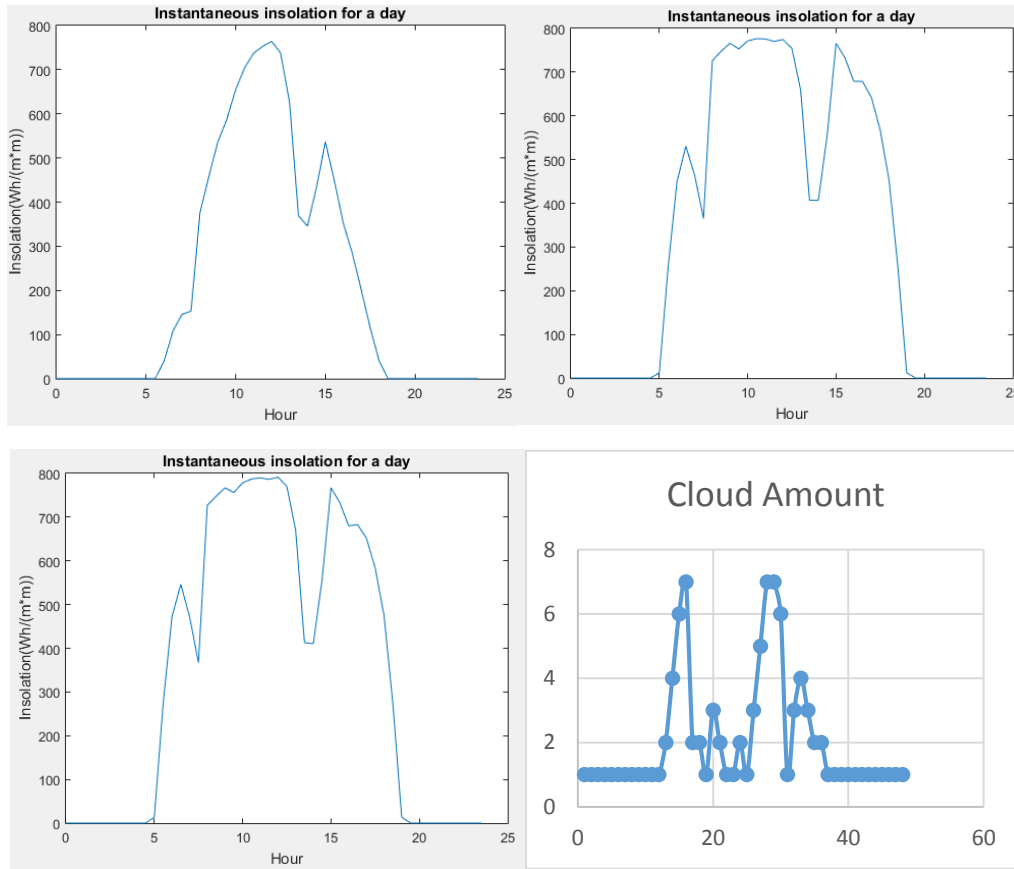


Fig.3.6.1.1 Instantaneous insolation for a day of fixed angle, one axis tracking, two axis tracking vs. cloud amount

Fig.3.6.1.1 presents the instantaneous insolation on 9<sup>th</sup> January. As it can be observed in the diagram, the instantaneous solar insolation is greatly affected at the point at which the cloud amount is peaked. A sharp decrease can be observed in the diagram of different configuration. The maximum insolation for fixed angle appears at solar noon, which is  $764 \text{ Wh}/\text{m}^2$ . However, the instantaneous solar insolation for both one-axis and two-axis tracking have a flat top. The increase of performance between two axis and one axis tracking is 4%. However, the cost of installing a two axis tracking system is much higher than the increase of performance. As a result, two axis tracking system is disregarded in the following analysis.

### 3.6.2 Weekly insolation analysis

The instantaneous insolation for a week is then plotted, the influence of cloud coverage can be observed in the diagram.

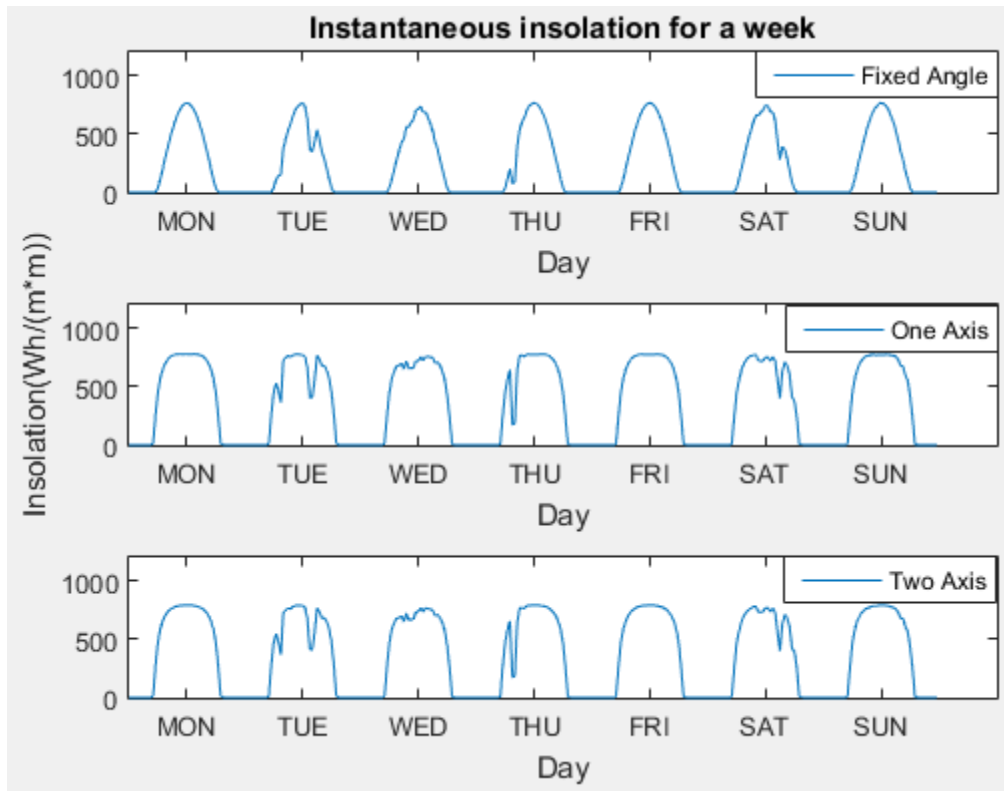


Fig.3.6.2.1 Instantaneous insolation for 3 cases over a week

### 3.6.3 Annually insolation analysis

The daily solar insolation is calculated by summing the product of the solar irradiance at each point and the minimum time interval. The resultant daily solar insolation is then compared with the peak sun hour provided. Peak sun hours is of the definition of the daily solar insolation. The area below the curve of instantaneous solar insolation is then reallocated to form a rectangle and peak sun hours is the equivalent time which the solar irradiance is  $1 \text{ kW}/\text{m}^2$  [10].

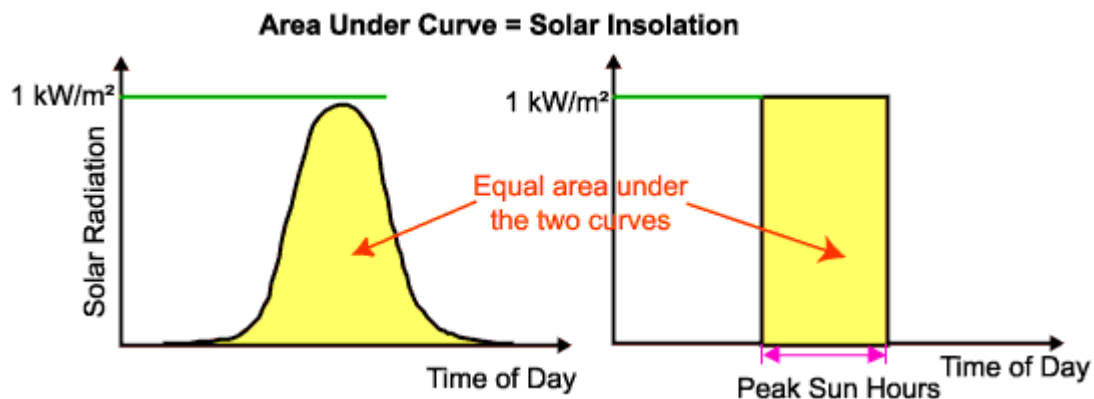


Fig.3.6.3.1 daily peak sun hours estimation

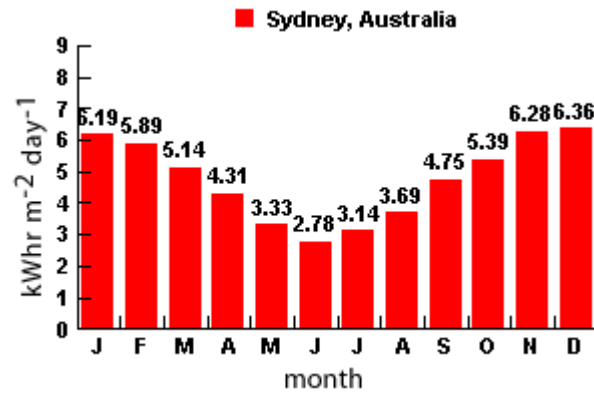


Fig.3.6.3.2 daily peak sun hours of Sydney

The curve of daily insolation fits the curve of the monthly average peak sun hours. The ripples in the curve suggest the climate change throughout the year. The peak of the curve appears in summer and the curve reaches the lowest point in winter, which is as predicted. The curve from July to September is a smooth line compared with other season in the year, which is due to the cloud coverage data is incomplete in this period. The accuracy of the estimation can be improved.

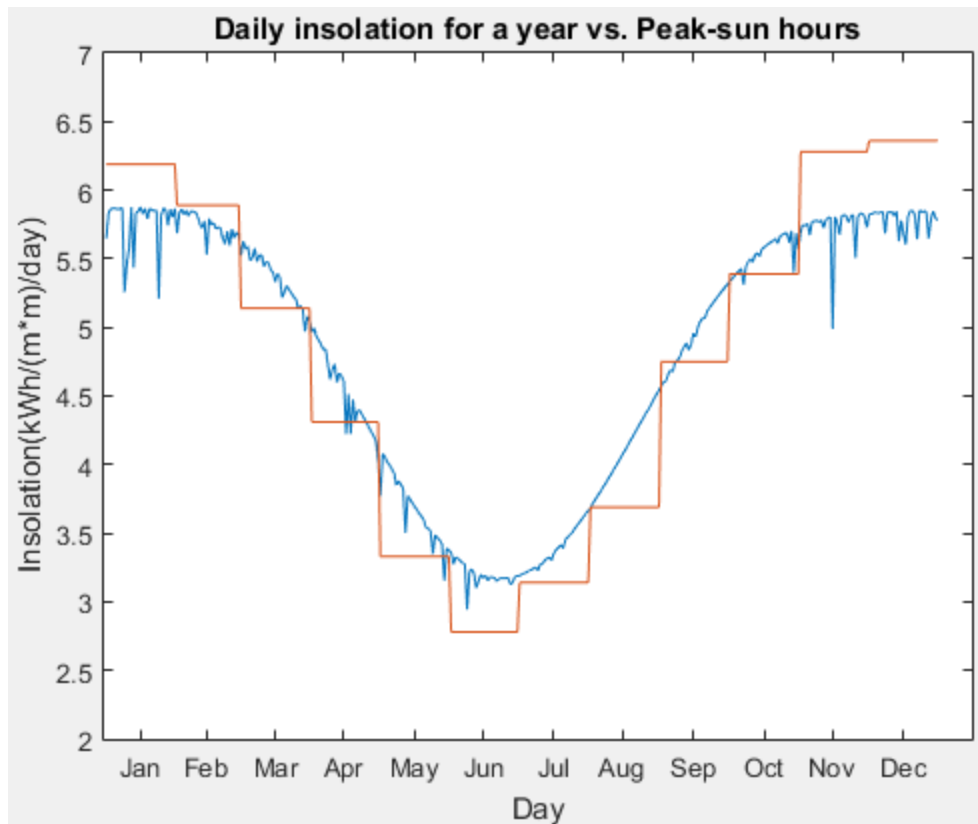


Fig 3.6.3.3. Daily insolation for a year vs. Peak sun hours, fixed angle

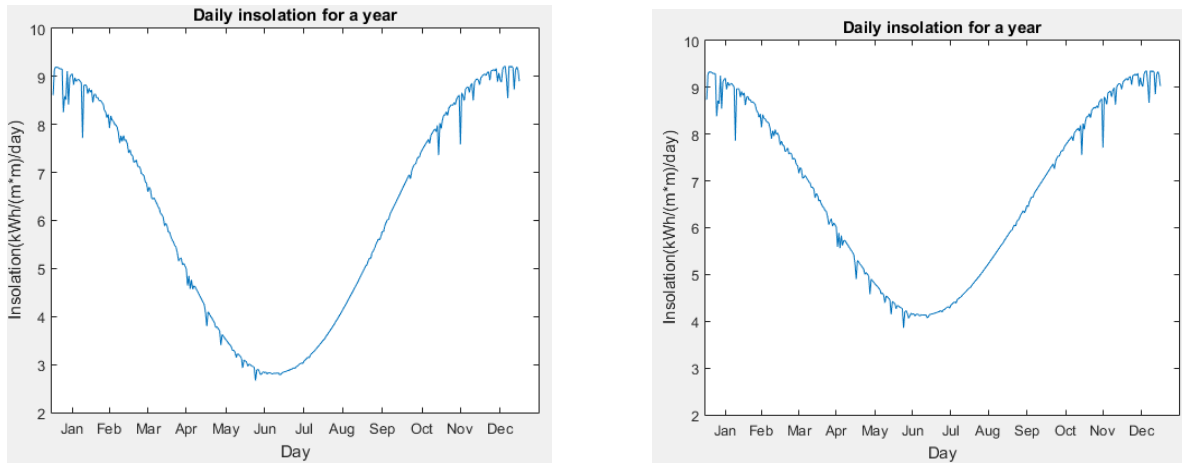


Fig.3.6.3.4 Daily insolation for a year vs. Peak sun hours, one and two axis tracking

The daily insolation of single axis tracking can greatly increase the performance of the solar panel. However, the cost of two axis tracking system is also significant. The economic feasibility is compared in later simulation.

### 3.6.4 Weekly PV-Output analysis

Since the impact of temperature is comparatively small and other losses at different time of the day is a factor directly multiplied to the result. The PV output is of the similar shape with the solar insolation.

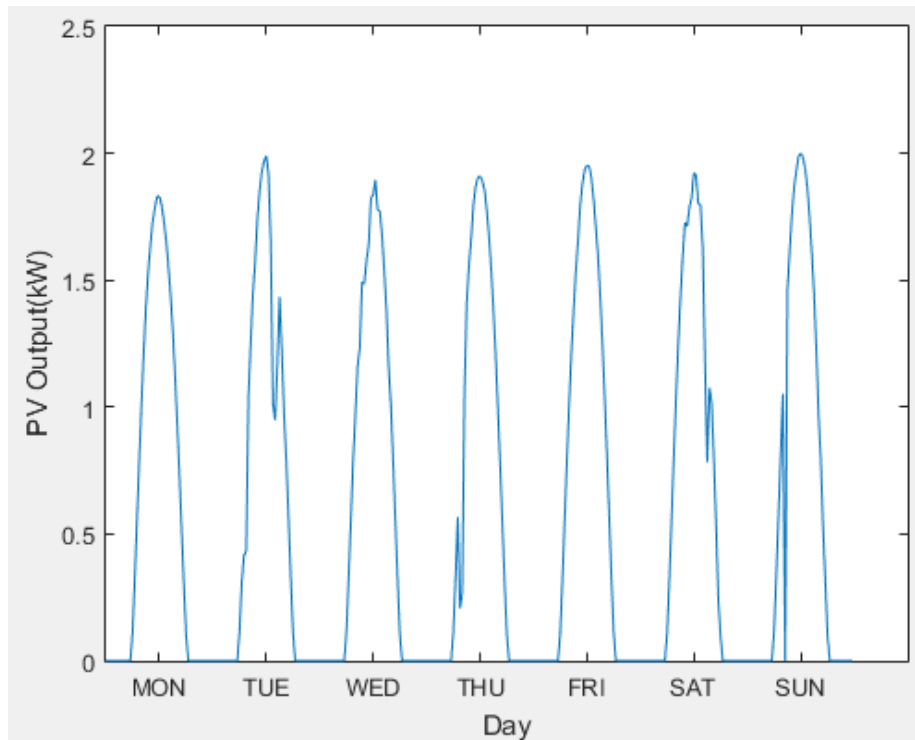


Fig.3.6.4.1 Instantaneous PV output over a week- 12 fixed panel

The PV output over the same week of 12 fixed angle PV panel is shown in Fig.3.6.4.1, as it can be observed, the PV output is basically proportional to the solar insolation. The daily peak PV output power is around 2kW

The number of PV panel is reduced by 2 and a single axis tracker is installed to compare the difference in the two cases. Notice that the output power is reduced, a basic prediction of the optimization result is generated, which will later be verified in section 7.2.

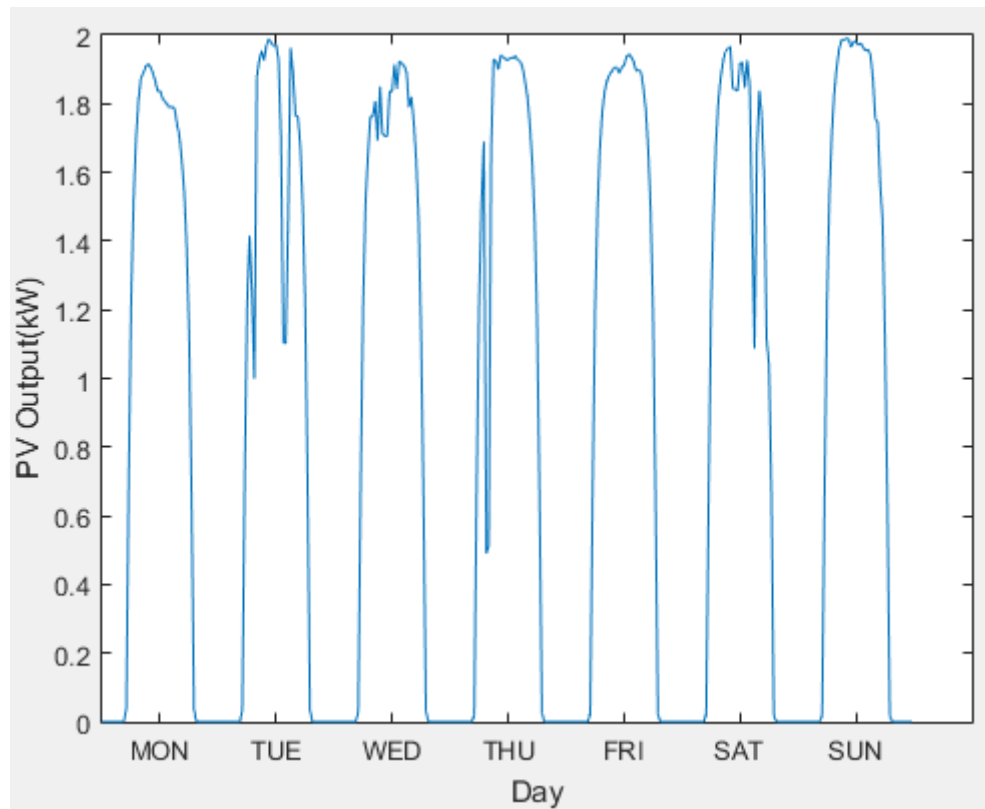


Fig.3.6.4.2 Instantaneous PV output over a week- 10 one-axis-tracking panel

## 4 Estimate the electric power requirements of the building

### 4.1 Method

The authors focus on designing PV system for a residential building owned by a young couple without kids. This building is located in southern Sydney metropolitan area in the suburb of Kingsgrove. It is worth mentioning that, the young couple who provided the electricity bill is currently living in an apartment. The data from the bill shows that their average daily usage is around 8.37 kWh/day. However, installing solar system, especially PV panels, on a rooftop of a house would be more convenient and reliable. Another important fact which also needs to be considered is that the consumption of electricity in a house is estimated to be greater than an

apartment. Therefore, the current average daily demand from the bill has been increased by 20% which becomes 10.044 kWh/day as well as the total estimated demand.

The power demand for this building could be roughly calculated by using the rated power of the major appliances and the estimated operating hours of each appliance throughout the day in order to obtain the consumption of a typical weekday and a typical weekend. Additionally, the calculated demand should be compared with the current electric bill to check the accuracy and then increase additional 20% of the consumption to receive the final estimated result.

The daily usage of power was divided into intervals of 30 minutes which results in 48 time intervals per day. This provided a higher degree of resolution for the demand data. However, several high-power electrical appliances are used less than 30 minutes, but their high power usage could not be ignored. In this case, the total value of the energy usage for the specific appliance would be calculated, and separated the power value into the related time period.

For example, the rated power of oven is 2000W and it would be used only one time per week for approximately 1.5 hours. Therefore, the energy used in 1.5 hours will be calculated, and then divided by 7 days and then divided by 2 to obtain an average value of power consumption per half-an-hour. The other high-power electrical appliances which might be used the same estimation method are kettle, microwave, heater and dryer.

In addition, the assumption of daily power consumption in spring and autumn are similar because of the similar climate conditions in these two seasons. Moreover, in order to simplify the estimation, air-conditioner would not be used during the seasons of spring and autumn and small amount of power will be consumed by slightly utilizing heater in spring and fan in autumn.

Other notable features of the power consumption

- The washing machine, the dryer and the vacuum cleaner will only be used once a week on weekend, between 10:30am and 12:30pm.
- Fridge is the only major appliance which is constantly operating.

## 4.2 Estimated results

Fig. 4.2.1 shows the daily power consumption of weekday in four seasons

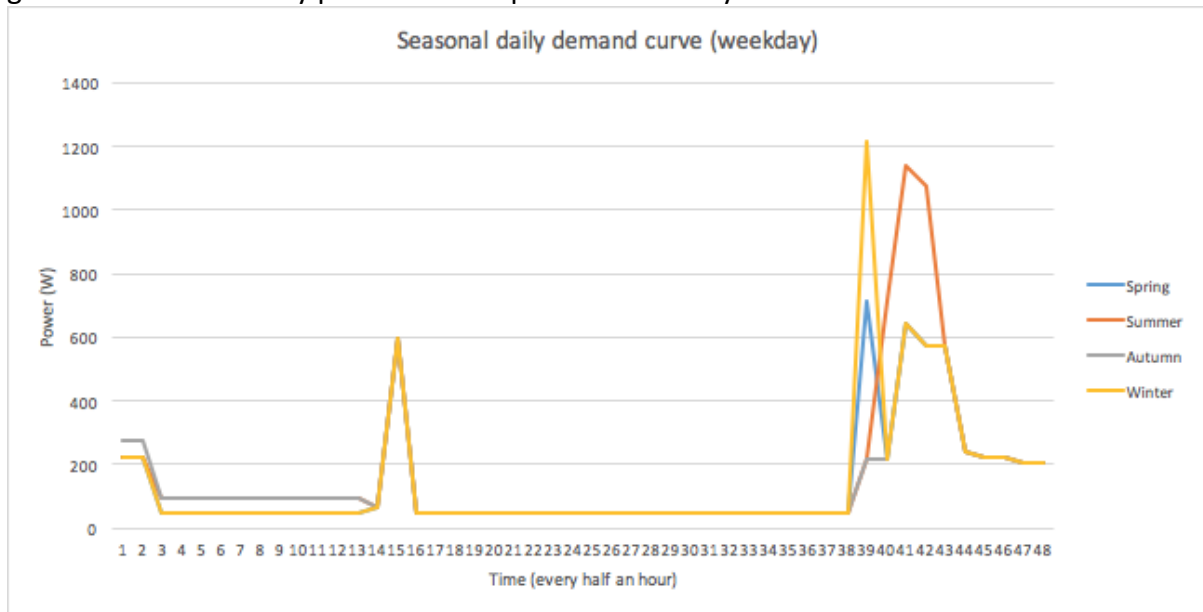


Fig. 4.2.1 The seasonal daily demand of weekday

Fig. 4.2.2 shows the seasonal daily demand of weekend

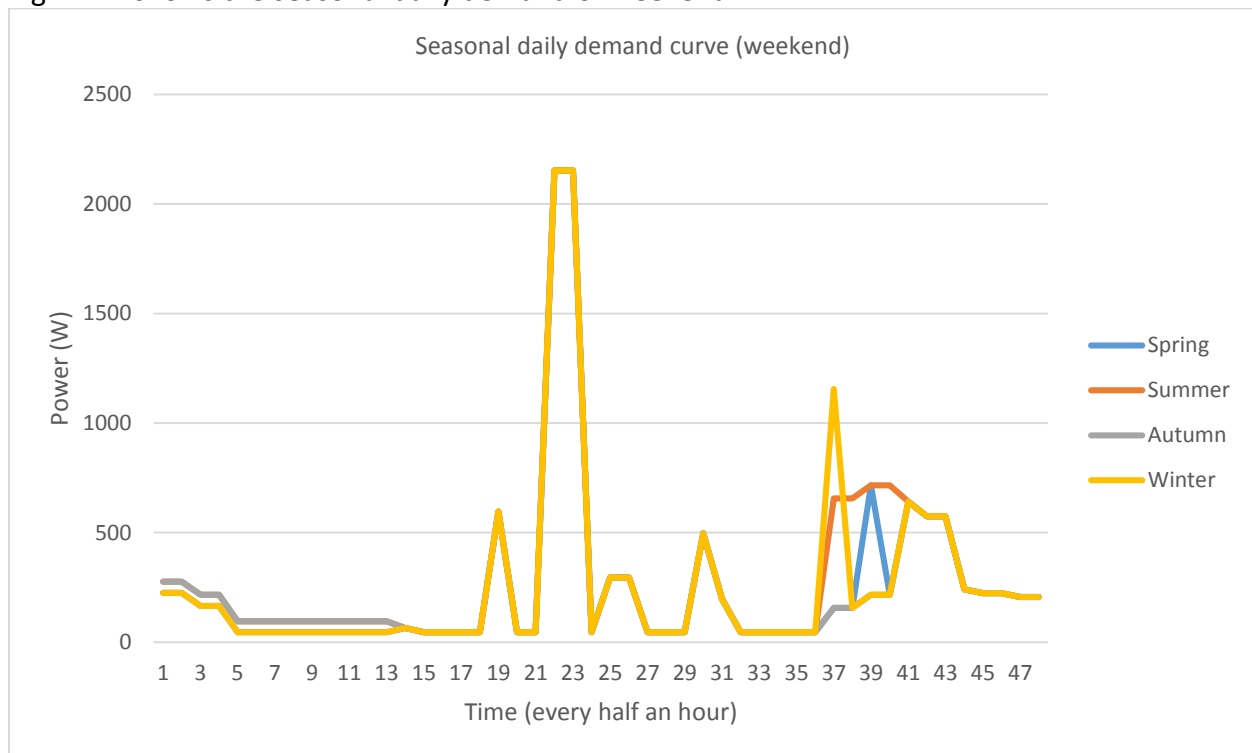


Fig.4.2.2 The seasonal daily demand of weekend

The above 2 graphs show the profiles of daily power consumption used in this project. For weekday, the large percentage of electricity application is located in shoulder and off-peak periods. However, on weekend, large amounts of electricity will be consumed during the noon.

Fig. 4.2.3 and Fig. 4.2.4 show the daily seasonal demand and the total seasonal demand respectively

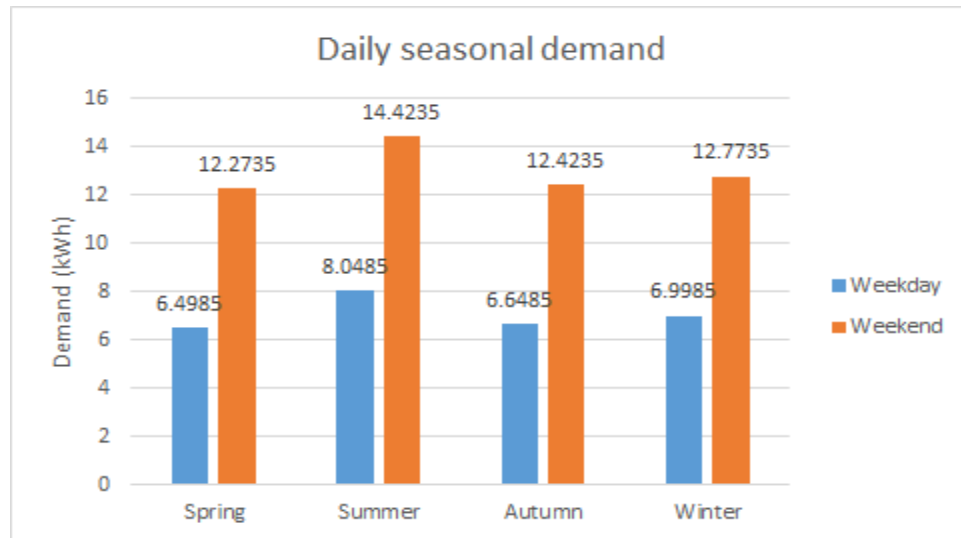


Fig.4.2.3 Daily seasonal demand

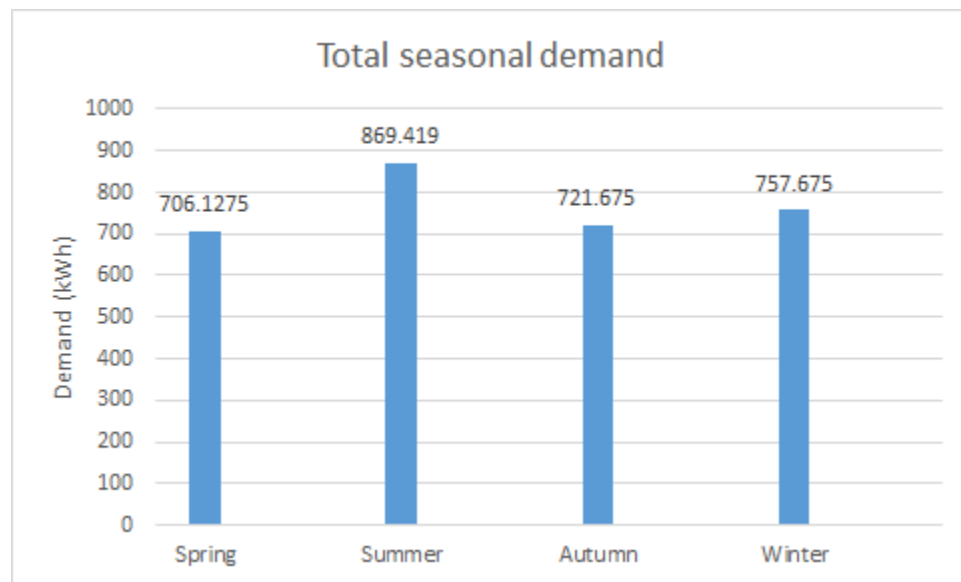


Fig.4.2.4 Total seasonal demand

According to the Fig. 4.2.3, it is obvious that the daily demand of weekend is twice as the daily demand of weekday since the household stays at home on weekends. Moreover, from Fig. 4.2.4, it is easy to find out that the demand in spring and autumn are quite similar. The difference of these two seasons is caused by the slightly use of heater in spring and the use of fan in autumn.

In addition, the consumption in summer is the largest among all the seasons because of the long-operating-time of air-conditioner. The demand of winter comes to the next due to the frequent use of heater.

## 5 Analyze retail and feed-in-tariff

### 5.1 Retail and feed-in tariff

This section discusses retail and feed-in tariff of different companies, which can provide an overview on the profitability of a solar battery system. The data and information are extracted from online resources [11]. By giving significant details of this residential house, the author selected 6 offers from 12 energy companies which provide residential electricity energy service. The 6 dominant energy companies, including AGL, Diamond Energy, Red Energy, Energy Australia, Origin Energy and Power direct can provide solar feed-in-tariff options. In order to gain the optimization selection, the data collection and comparison are shown as below.

The below comparison chart is an indicator

COMPANY	PEAK TIME (¢/kWh Inc. GST)	OFF PEAK TIME (¢/kWh Inc. GST)	SHOULDER TIME (¢/kWh Inc. GST)	SUPPLY CHARGE (¢/day Inc. GST)
AGL	51.117	10.747	19.646	89.353
Diamond energy	45.65	10.78	18.48	88.00
Red energy	45.10	10.23	16.50	87.516
Energy Australia	46.134	10.89	19.316	85.36
Origin energy	50.611	11.440	20.262	90.838
Power direct	51.084	10.714	19.613	89.353

Table 5.1.1. Comparison of electricity price with 6 companies

Extra electricity produced by solar panel which cannot be used by residential requirement can be sold to energy companies. The solar Feed-in-Tariff are compared as below.

COMPANY	PRICE (¢/kWh Inc. GST)
AGL	5.10
Diamond energy	8.00
Red energy	5.00
Energy Australia	5.10
Origin energy	6.00
Power direct	7.70

Table 5.1.2. Feed-in-tariff

## 5.2 Proposal

Fig. shows the seasonal demand of three periods per week

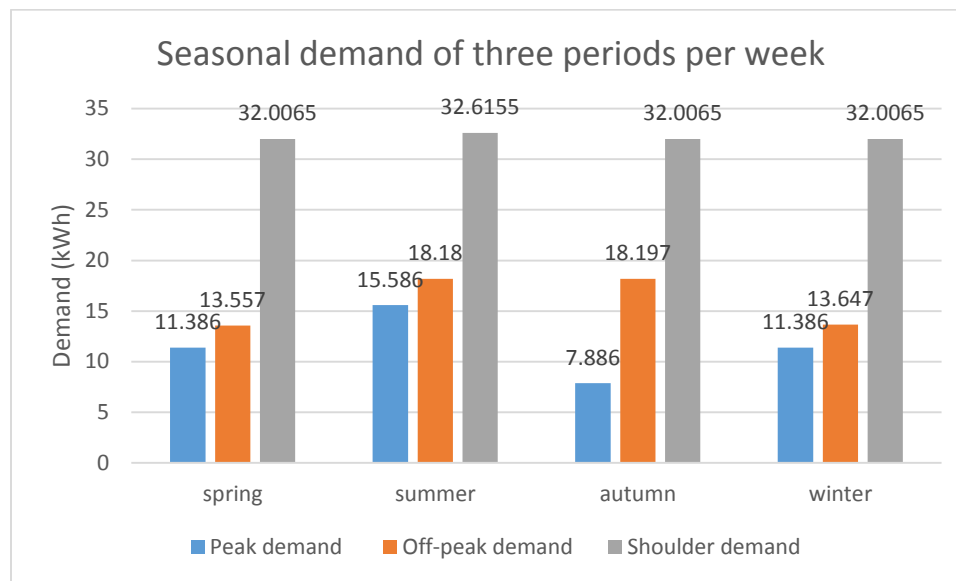


Fig.5.2.1 Seasonal demand of three periods per week

The graph above shows the seasonal demand of three periods per week because the demand of remaining weeks for each season are the same and approximately 80% of the total demand is located in shoulder and off-peak periods, especially in shoulder time. Specifically, the majority of electric alliances will be used in shoulder and off-peak periods because the young couple need to work during the weekday between 8am and 7pm. In another way, small amounts of electricity would be consumed in the peak hours. Compared with the demand on weekdays, even the peak time consumption would be increased on weekends, but the total demand of it would not significantly influence the estimation.

The electricity of the household is currently provided by origin energy. Based on the electrical demand in this case is relatively high in off-peak and shoulder periods compared with the demand of peak time, switching to another company will be a reasonable decision for saving money. According to the comparison of electricity price in Table 5.1.2, only three companies should be considered which are Diamond Energy, Red Energy and Energy Australia. For instance, due to the calculation (including peak, off-peak, shoulder and supply charge), the cost of Diamond Energy for a week in summer is \$21.26/week, the cost of Red Energy for a week in summer is \$20.4/week and the cost of Energy Australia for a week in summer is \$21.45/week. Thus, it is obvious that switching to red energy will reduce the electricity bill, as the tariff of Red Energy in shoulder and off-peak period is the lowest among all the companies.

## 6 Design the PV/battery system

Based on the information collected and analysed in the previous sections, this section discusses the setup of PV-battery system. The typical devices which would be considered in this project are PV panels, inverters and batteries.

NOTE: All the information, including specifications and unit price of the hardware listed below is real data gathered from [12] [13].

In addition, extreme situations which could have significant influences on the performance of parts of the chosen devices are also discussed in this section.

### 6.1 Principles on choosing hardware

To reasonably narrow the range of selection, the following principles are applied:

1. The capacity of the system should just fit with the demand of the basic use of this family. Ideally, the output from the PV-battery system should cover the total electricity demand of the family and no redundant electricity is sent back to the grid.
2. Based on the prediction that meets the above requirement, choose the most economical sets of the hardware to shorten the payback period of the family.

### 6.2 PV panels

According to Section 4.1, the electricity demand of the family is around 10kWh per day. Since the family use electricity in both day time and night time, two approaches of how the electricity flows from the PV panels to the family's appliances are summarized as below.

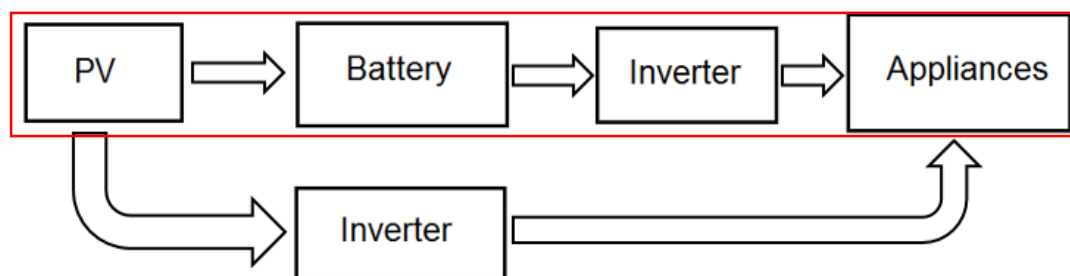


Fig. 6.2.1 Two approaches to supply electricity consumption

Since the couple are both working in weekdays, the consumption in daytime is relatively low. The following extreme situation needs to be taken into consideration: there is no sunlight when the household consume electricity, in which during the night and the next early morning the household only consume the power saved in the battery, as shown in the red area in the above Fig. 6.2.1.

In this case, the consumption amount of the whole appliances is estimated to be 10 kWh, consider the inverter efficiency (96.6%) and battery efficiency (90%), the PV output energy to be saved in the battery should be  $10\text{kWh} \div 96.6\% \div 90\% = 11.50\text{kWh}$ .

According to [14], the typical PV output power needed for a daily production of 10kWh is 2kW to 3kW, also consider the possible losses and constraints during the producing process, solar panel sets which can provide output power around 3kW are compared in later section.

To reach the required output power of 3kW, the range of selection is narrowed down as follow:

- 10 panels of 250W PV panel with trackers (aims to get the maximum solar insolation in the production process)
- 12 panels of 250W PV panel
- 14 panels of 250W PV panel.

Some key values of the PV panels are given below.

#### Electrical Characteristics

STC	STP250-20/ Wd	STP245-20/ Wd	STP240-20/ Wd
Maximum Power at STC (Pmax)	250 W	245 W	240 W
Optimum Operating Voltage (Vmp)	30.7 V	30.5 V	30.2 V
Optimum Operating Current (Imp)	8.15 A	8.04 A	7.95 A
Open Circuit Voltage (Voc)	37.4 V	37.3 V	37.2 V
Short Circuit Current (Isc)	8.63 A	8.52 A	8.43 A
Module Efficiency	15.4%	15.1%	14.8%
Operating Module Temperature	-40 °C to +85 °C		
Maximum System Voltage	1000 V DC (IEC)		
Maximum Series Fuse Rating	20 A		
Power Tolerance	0/+5 %		

STC: Irradiance 1000 W/m<sup>2</sup>, module temperature 25 °C, AM=1.5;  
Best in Class AAA solar simulator (IEC 60904-9) used, power measurement uncertainty is within +/- 3%

Fig. 6.2.2 SUNTECH WD 250W PV panel characteristics

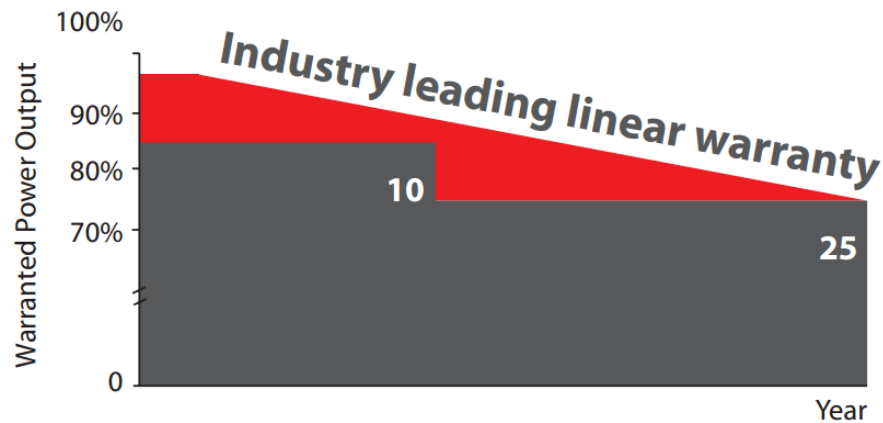


Fig. 6.2.3 PV panel linear output warranty

- **SUNTECH WD 250W POLY SOLAR PANEL**  
 Rated power output: 250W  
 Module efficiency: 15.4%  
 Module area: 1.64 m<sup>2</sup>  
 Unit price: AU \$314.00  
 Product warranty: 10 years material and workmanship  
 Performance guarantee: 25 years power output  
 Power output degradation: 1) 1st year: 97%, 2) After 2nd year: 0.7% annual degradation, 3) 80.2% for 25 years  
 Temperature Coefficient ( $P_{mp}$ ): -0.43 %/°  
 [15]
- **Ecosolargy ECO250S156M-60 mono Black**  
 Maximum power output: 250W  
 Module efficiency: 15.40%  
 Module area: 1.64 m<sup>2</sup>  
 Unit price: US \$240.00, i.e. AU \$336.00  
 Product warranty: 10 years material and workmanship  
 Performance guarantee: 25 years power output  
 Power output degradation: 1) 1st year: 97%, 2) After 2nd year: 0.7% annual degradation, 3) 80.2% for 25 years

- Module Specification: ecoSology Lotus ECO250S156M-60
- STC DC Watts Maximum Power P<sub>max</sub>: 250 W
- PTC DC Watts Maximum Power P<sub>max</sub>: 222 W
- AC kWh generated based on NREL PV Watts estimate
- AC power monthly: 31.25 kWh
- AC power per year: 375 kWh
- Module Efficiency: 15.40%
- Maximum Power Voltage V<sub>mp</sub> (V): 31.0V
- Maximum Power Current I<sub>mp</sub> (A): 8.07A
- Open Circuit Voltage V<sub>oc</sub> (V): 37.80V
- Short Circuit Current I<sub>sc</sub> (A): 8.51A
- Maximum system voltage: 600V UL, 1000V IEC
- Maximum series fuse rating: 15A
- Cells per module: 60
- Cell Type: Mono-crystalline silicon
- Frame: Anodized Aluminum Alloy, Black on Black
- Glass: Self-cleaning, high transparent tempered solar glass
- Dimensions: 64.57 x 39 x 1.57 inches
- Weight: 40.8 lbs
- Connector Type: MC4 compatible
- Output cables: 35.43 inches
- Product Warranty: 10 years material and workmanship
- Performance Guarantee: 25 years power output
- Fire Safety Classification: Class C
- Certifications: UL 1703, CEC, IEC 61215, IEC/EN 61730
- Operating Temperature Range: -40F to 1+185F
- Front Load (snow) Test: 5400 Pa (112.8 PSF)
- Rear static load (wind) test: 2400Pa
- Hailstone impact test: 1 inch hail at 43 MPH from 1m distance

Fig. 6.2.4 Ecosology ECO250S156M-60 PV panel characteristics

According to Section 2.1, the rooftop area of the target house is 52 m<sup>2</sup>, as 14×1.64=22.96m<sup>2</sup>, plus a space margin for the installation and maintenance, 22.96 m<sup>2</sup> ×120%=27.55 m<sup>2</sup> <<52m<sup>2</sup>, therefore, the area is not a constraint here.

To choose suitable PV panel module, compare the key specifications of these two panels:

Module	SUNTECH WD 250W	Ecosology ECO250S156M-60
Efficiency (%)	250W	250W
P <sub>max</sub> at STC	15.4%	15.4%
Open circuit voltage	37.4V	37.8V
Short circuit current	8.63A	8.51A
NOCT	45±2°C	45±2°C
Module area	1.64m <sup>2</sup>	1.64m <sup>2</sup>

Product warranty	10 years material & workmanship	10 years material & workmanship
Performance guarantee	25 years power output	25 years power output
Power output degradation	1) 1st year: 97%, 2) After 2nd year: 0.7% annual degradation, 3) 80.2% for 25 years	1) 1st year: 97%, 2) After 2nd year: 0.7% annual degradation, 3) 80.2% for 25 years
Price	AUD\$314	AUD\$336

Table. 6.2.1 Comparison between PV panels

As it can be observed from the table above, the key data of the two listed PV panels are very close. For the economical causes, SUNTECH WD 250W shown in Fig. 6.2.5 is chosen to minimize the initial cost.



Fig. 6.2.5 SUNTECH WD 250W

## 6.3 Inverter

To fit different PV output power requirements ( $10 \times 250\text{W} = 2.5\text{kW}$ ,  $12 \times 250\text{W} = 3\text{kW}$ ,  $14 \times 250\text{W} = 3.5\text{kW}$ ), three different inverters are to be used: 2.5kW, 3kW, 3.5kW.

Some key values of the PV panels are given below.

- ABB Inverter Aurora Uno 2.5  
 Nominal DC power input: 2,500 watts  
 Maximum efficiency: 96.6%  
 Unit price: US \$1,550.00, i.e. AU \$2170.00  
 Warranty: 10 years, optional extended warranty up to 20 years



- Fronius IG Plus A 3.0-1 UNI  
Nominal DC power input: 3,000 watts  
Maximum efficiency: 96.2%  
Unit price: US \$1,600.00, i.e. AU \$2240.00  
Warranty: 10 years, optional extended warranty up to 20 years



- ABB Inverter Aurora PVI 3.6  
Nominal DC power input: 3,600 watts  
Maximum efficiency: 97.0%  
Unit price: US \$1,750.00, i.e. AU \$2450.00  
Warranty: 10 years, optional extended warranty up to 20 years



- Solar Inverter Model: ABB Aurora Uno 2.0, UNO-2.5-I-OUTD-US, UNO-2.5-I-OUTD-S-US, UNO-2.5-OUTD-S-US-A
- **DC Power Input**
- Nominal Output Power: 2,500 watts
- Maximum Output Power: 2,750 watts
- Maximum Voltage: 520V
- Start-up Voltage: 200V
- MPPT Voltage Range: 205V-470V
- Maximum Usable Current: 12.8 Amps
- Maximum Open Circuit Current: 15 Amps
- **AC Power Output**
- Voltage Range: 183V - 304V
- Grid Frequency: 60Hz
- Maximum Current: 12A
- Maximum Efficiency: 96.6%
- **Mechanical Specifications**
- 5.5" LED Graphic Display
- Enclosure: NEMA 4X outdoor rated
- Weight: 42.5 lbs
- Dimensions: 30.3 x 14.4 x 6.3 inches
- Warranty: 10 years, optional extended warranty up to 20 years
- Certifications: UL1741

Fig. 6.3.1 ABB Inverter Aurora Uno 2.5 characteristics

- Model: Fronius IG-Plus-A-3.0-1 UNI, # 4,210,121,800
- Application: Grid Tied Inverter
- Maximum Efficiency: 96.2%
- CEC Weighted Efficiency: 95.5%
- Cooling: Forced Convection
- Country of Origin: Austria
- Enclosure Type: NEMA 3R
- Maximum DC Input Current: 14.0 Amps
- Maximum DC Input Power: 3,450 Watts
- Maximum DC Input Voltage: 600.0 Volts
- Maximum Output Current: 12.5 Amps
- Maximum Output Power: 3,000 Watts
- Nominal AC Output Power: 3,000 Watts
- Nominal AC Output Voltage: 240.0 Volts
- Nominal Output Frequency: 60 Hz
- Number of DC Input Terminals: 6.0
- Dimensions: 26.5 x 17.1 x 9.9 inches
- Weight: 55 lbs
- Certifications: UL 1741-2010, IEEE 1547-2003, IEEE 1547.1, ANSI/IEEE C62.41, FCC Part 15 A & B, NEC Article 690, C22. 2 No. 107.1-01

Fig. 6.3.2 Fronius IG Plus A 3.0-1 UNI characteristics

- Solar Inverter Model: ABB PVI-3.6-OUTD-S-US-A, PVI-3.6-OUTD-S-US, PVI-3.6-OUTD-US
- **DC Power Input**
- Maximum STC Rated PV power: 6,000 watts DC; 2 channels @ 3,000 watts
- Maximum Efficiency: 97.0%
- Maximum Input Voltage: 600 Vdc
- Minimum Input Voltage: 120 Vdc
- Minimum Start Voltage: 200 Vdc
- MPPT Voltage Range (Max): 530.0 Volts
- MPPT Voltage Range (Min): 120.0 Volts
- Maximum DC Input Current: 20 Amps
- Maximum usable current per channel: 16A
- Maximum short circuit current limit per channel: 20A
- **AC Power Output**
- Maximum AC Power Output: 4,000 watts @ 240Vac
- Nominal AC Power Output: 3600 watts
- CEC Weighted Efficiency: 96.0%
- AC Output Voltage: 208V, 240V, 277Vac
- Nominal AC Output Voltage: 240.0 Volts
- Maximum Output Current: 16 Amps @ 240Vac
- Maximum AC OCPD Rating: 20A @ 240Vac
- Nominal Output Frequency: 60.0
- Enclosure Type: NEMA 4X, outdoor rated
- Dimensions: 33.8 x 12.8 x 8.7 inches
- Weight: 21.3 lbs
- Cooling Method: natural convection
- Operating Temperature Range: -40F to +140F
- Warranty: 10 years, optional extended warranty up to 20 years
- Country of Origin: USA

Fig. 6.3.3 ABB Inverter Aurora PVI 3.6 characteristics

Based on the residential nature of this family and the expectation of short payback period, only 1 inverter will be used in the system.

## 6.4 Battery system

Throughout the investigation of the daily activities of the household, it is found that the couple usually consumes majority of the electricity in the morning and evening during weekdays. In weekends, they electricity demand is spread over the whole day which emphasize the necessity of battery in the system.

To strike a balance between performance and lifespan of the battery, deep cycle battery—AGM (Absorbent Glass Mat) is chosen finally. The specification of the chosen battery is shown as below:

- UPG UB-GC2 AGM Battery
- Voltage: 6 VDC
- Amp Hours: 200 Ah
- Type: AGM (Absorbent Glass Mat)
- Maximum efficiency: 90%
- Unit price: US \$230.00, i.e. AU \$322.00
- Life expectation: approximately 10-13 years



Fig. 6.4.1 UPG UB-GC2 AGM Battery characteristics

As analysed in Section 6.2, the battery capacity needs to cover 11.5kWh, therefore, at least 10 units of AGM 1.2kWh battery is needed to make a 12kWh battery bank. However, considering the efficiency of the battery bank and possible losses, together with the fact that 11.5kWh is just for the average use of the whole year, peak demand will appear from time to time, the following 3 different options are compared in later simulation:

- Battery system of 10 unit AGM 1.2kWh battery
- Battery system of 12 unit AGM 1.2kWh battery
- Battery system of 14 unit AGM 1.2kWh battery

## 6.5 Charging controller

- Xantrex C35 Charge Controller  
 Battery Voltage: 12V - 24V DC  
 Maximum Input voltage: 55V DC  
 Load current: 35A  
 Peak current: 85A  
 Enclosure type: Ventilated  
 Price: US \$99, i.e. AU \$138.6



- Battery Voltage: 12V - 24V DC
- Maximum Input voltage: 55V DC
- Load current: 35A
- Peak current: 85A
- Enclosure type: Ventilated
- Enclosure material: Powder coated steel
- Device mounting: wall mounted, vertical
- Wire gauge: #10 AWG
- Warranty: 2 Years
- Weight: 3 lbs
- Dimensions: 8" x 5" x 2.5"
- Mounting: Vertical wall mount - indoor only
- Enclosure: Indoor, ventilated, powder coated steel with 3/4" and 1" knockouts
- Temperature operating Range: 32 F to 104 F
- UL and cUL Listed C Series controllers are listed by UL to exacting UL 1741 and cUL CSA 22.2 107.1-95 standards. C Series controllers are also CE compliant (European countries) and are designed to CTIK standards (Australia). Their current ratings are "real world" and do not have to be derated to comply with USA NEC 125% over-current requirements.
- As a DC load controller, the C Series has a low voltage disconnect warning indicator and field adjustable set points that govern automatic low and high voltage disconnect
- Manual reset switch for emergency low voltage operation
- The C Series automatically directs extra power to a dedicated load, such as an electric water heater, and ensures batteries are never over charged

Fig. 6.5.1 Xantrex C35 Charge Controller characteristics

The choice of charge controller is based on the input and output current limit and economic feasibility. The chosen charge controller meets the requirement and can provide a comparatively short payback period.

## 6.6 Connection of the PV/battery system



Fig. 6.6.1 Installation of the PV panels on the rooftop



Fig. 6.6.2 Installation of the PV panels on the single axis tracker



Fig. 6.6.3 Installation of the battery bank



Fig. 6.6.4 Installation of the inverter

The placement of the PV panels is shown in Fig.6.6.1 and Fig.6.6.2 either fixed on the rooftop or on the single-axis trackers.

The connection of the PV/battery system is shown in the diagram below.

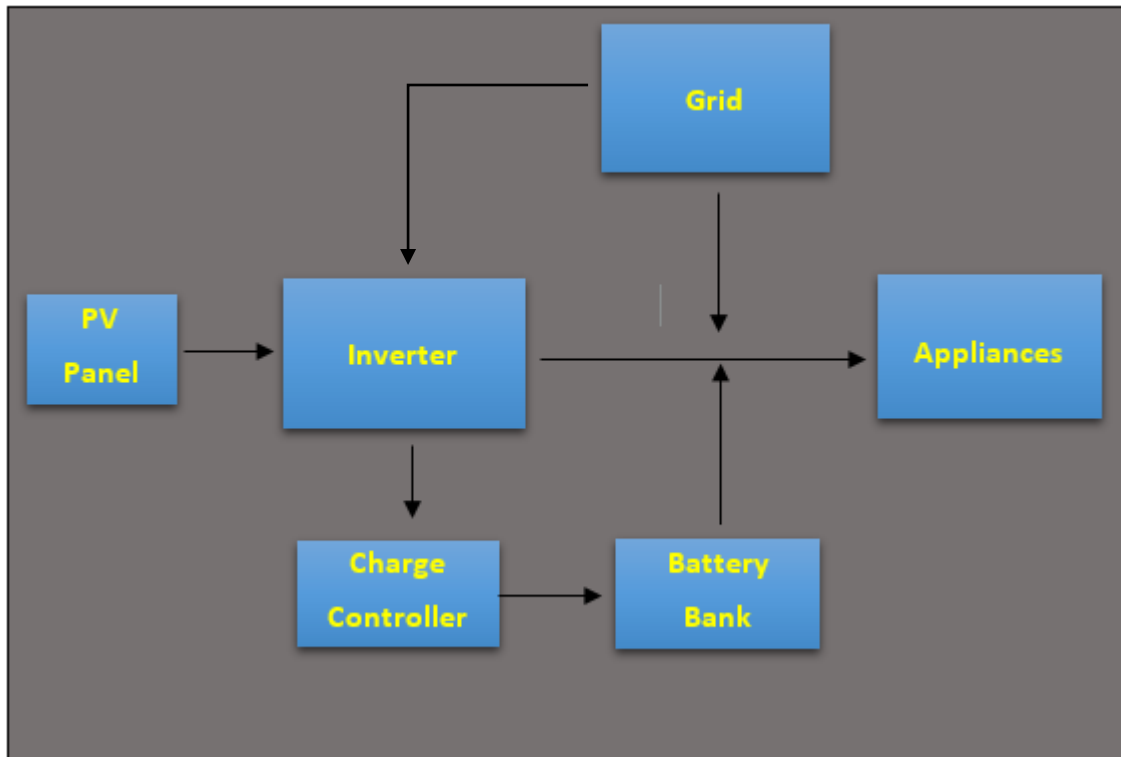


Fig. 6.6.5 Connection diagram of the PV/battery system

The operating principles in this system:

- The electricity initially goes from the PV panels to the home appliances
- In daytime, the extra electricity goes through the charge controller to the battery bank, saving for the night demand use
- If the electricity generated by the PV panels covers the total demand in the family, the redundant energy from both the PV panels and the battery bank goes through the inverter to the grid
- If the electricity is not enough for the whole day demand, for example, during rainy or cloudy days, then the battery will get charged from the grid in the off-peak time.

## 6.7 Consideration of extreme situations on equipment performance

This section checks the equipment rating for extreme situations (e.g. temperature effect on the min/max voltage of the PV panel and whether it violates the inverter's limits, etc.);

In the practical design, the extreme situation should be considered both for the performance of the system and safety issues.

In this project, since the performance of the PV panels would be influenced by the operating temperature, it is important to limit the voltage output of the PV panels to not exceed the range of the inverter. According to the Section 6.2 and 6.3, the maximum input voltage and current cannot exceed the limitations of the chosen inverters.

## 6.8 Consideration of the charging constraints of the battery system

Fast charging and discharging will have a great impact on the life cycle of the battery, so the charging and discharging rate should be carefully taken into account of the system design.

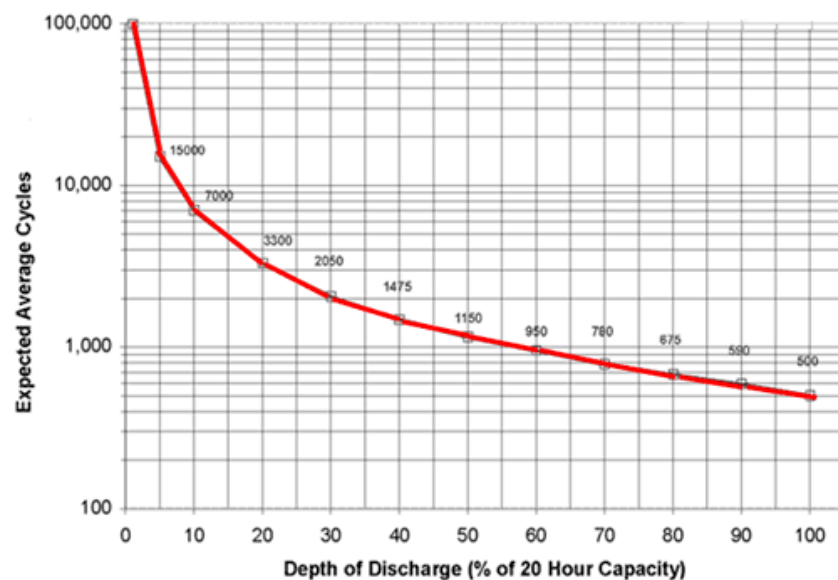


Fig. 6.8.1 Relationship between Depth of Discharge and life cycle

However, in this particular case, the family uses relatively low energy in the day time, so the battery charging rate does not need to be set to an excessive value.

In addition, according to [16], the AGM battery can be fully charged quickly and discharged deeply.

Application	Charge Voltage(V/Cell)			Max.Charge Current
	Temperature	Set Point	Allowable Range	
Cycle Use	25°C(77°F)	2.45	2.40~2.50	0.35C
Standby	25°C(77°F)	2.325	2.30~2.35	

Final Discharge Voltage V/Cell	1.75	1.70	1.60	1.30
Discharge Current(A)	$0.2C > (A)$	$0.2C < (A) < 0.5C$	$0.5C < (A) < 1.0C$	$(A) > 1.0C$

Fig.6.8.2 Charge Current & Final Discharge Voltage

## 6.9 Determine the optimal solution

The decision is made by the simulation of the EMS system in Section 7 and by calculating the related cash flows in Section 8.

# 7 Design the energy management system

## 7.1 Theory of energy management system design

The intelligent energy management system is designed to minimize the electricity bills of the chosen household on a daily basis and is examined for a year to determine the annual saving compared with the electricity bill before the installation of the PV system. The power demand estimated for weekdays and weekends in different seasons are allocated to form the power demand of a year according to the calendar of year 2013. The retail and feed-in tariff on each day is repeatedly outputted to the same excel file. The EMS Matlab file extracts data from the generated yearly data and optimally minimize the yearly electricity bill by accessing the data day by day using a for loop.

The EMS contains solar panel, battery and grid. Factors that are taken into consideration include power consumption, PV output, retail tariff and feed-in tariff which are all with half-hourly resolution). To further improve the accuracy of the estimation, interpolation is performed between the discrete data to add a trend line to all the data points.

The battery plays a dominant role in the optimal solution of the sustainable energy system. For each day, the start and end state of charge of the battery is pre-determined to simplify the task. The size of the battery is optimized by the program in which it needs to adequately cover the daily power demand but no unnecessary storage is required. The maximum charge and discharge rate greatly affect the performance of the battery. If the discharge rate is lower than the power demand the system has to draw electricity from the grid. If the charge rate is lower than the PV output, there is a chance that the generated cannot be stored to the battery for later use and has to be delivered to the grid.

The number of battery and number of PV panel are both determined by the optimization program. The resultant annual saving for each case is then compared in the cash flow analysis.

The decision factor of the optimization contains [17]

- $p_g^{+/-}$ : power flowing from/to grid,
- $p_b^{+/-}$ : battery charge/discharge power,
- $p_b^g$ : power flowing from battery to grid,
- $p_b^d$ : power flowing from battery to demand,
- $d_g \in \{0, 1\}$ : direction of grid power flow (0: demand→grid, 1: grid→demand),
- $d_{pv} \in [0, 1]$ : proportion of PV power flow (0: all PV power flows to grid, 1: all PV power flows to demand),
- $s_b \in \{0, 1\}$ : battery charging status (0: discharge, 1: charge),
- $e_b$  battery state of charge.

The optimization program is to minimize the daily cost of electricity bills, which is shown in the formula below:

$$C_{x-day}^T = \sum_{t=1}^n (p_{g,i}^+ c_{g,i} - p_{g,i}^- c_{PV})$$

The result of  $C_x^T$  is then accumulated through a year to determine the yearly saving:

$$Saving \text{ per year} = C_{x-year}^T - original \text{ cost}$$

Where the original cost is estimated by multiplying the half-hourly power demand with the retail tariff at the corresponding time:

$$original \text{ cost} = power \text{ demand} * retail \text{ tariff}$$

The schematic diagram of the power flow of the energy management system is shown below:

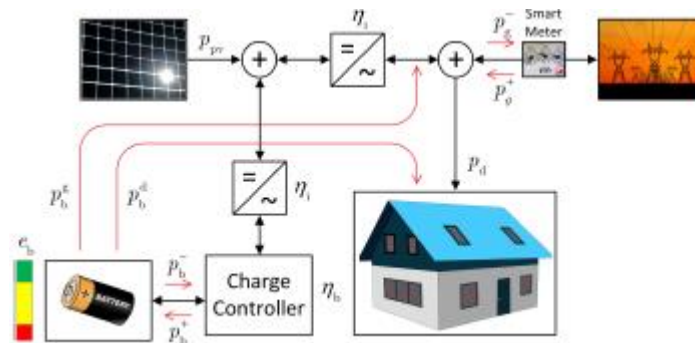


Fig. 7.1.1 Schematic diagram and the power flow of the energy management system

The system contains several equality constraints and inequality constraints, for instance, the power flowing from the battery is the combination of the power flowing from the battery to the grid and demand. The power flowing from the grid is the amount of demand that cannot be covered by the battery due to the capacity and the discharging rate of the battery. The power

flowing to the grid is the combination of the power discharged from the battery to the grid and the power generated by the PV panel exclude the power delivered to the demand. At any time point of the day, the state of the battery is the accumulation of the charged and discharged energy. The equality constraints described above are listed below:

o equality constraints:

$$\begin{aligned}
 p_{g,t}^+ &= p_{d,t} - \eta_i (\eta_b p_{b,t}^d + d_{pv,t} p_{pv,t} - p_b^+) \\
 p_{g,t}^- &= \eta_i (\eta_b p_{b,t}^g + (1 - d_{pv,t}) p_{pv,t}) \\
 p_{b,t}^- &= p_{b,t}^d + p_{b,t}^g \\
 e_b^t &= e_b^{t-1} + \Delta t (p_{b,t-1}^+ - p_{b,t-1}^-) \\
 e_{b,1} &= e_b^{\text{start}} \\
 e_{b,n} &= e_b^{\text{end}}
 \end{aligned}$$

The equality constraints and inequality constraints are then examined by a mixed-integer linear program, the mixed integer linear program is of the form:

$$\begin{aligned}
 &\underset{x_r, x_b}{\text{minimise}} && c^T x \\
 &\text{subject to} && \underline{x}_r \leq x_r \leq \bar{x}_r \\
 & && Ax \leq b \\
 & && x_b \in \{0, 1\}^{n_b} \\
 & && x_r \in \mathbb{R}_{\geq 0}^{n_r}
 \end{aligned}$$

## 7.2 Optimization result analysis

### 7.2.1 Result on 1st January, 2013— summer weekday

As it can be observed in the diagram, the electricity demand is greatest between 6pm and 10pm, in which the electricity is mostly provided by the battery. During the day time, the battery is charged with small amount of PV output to the demand only to supply the power for the fridge. There is only small amount of electricity drawn from the grid in which the maximum discharge rate of the battery is reached and extra electricity has to be drawn from the grid.

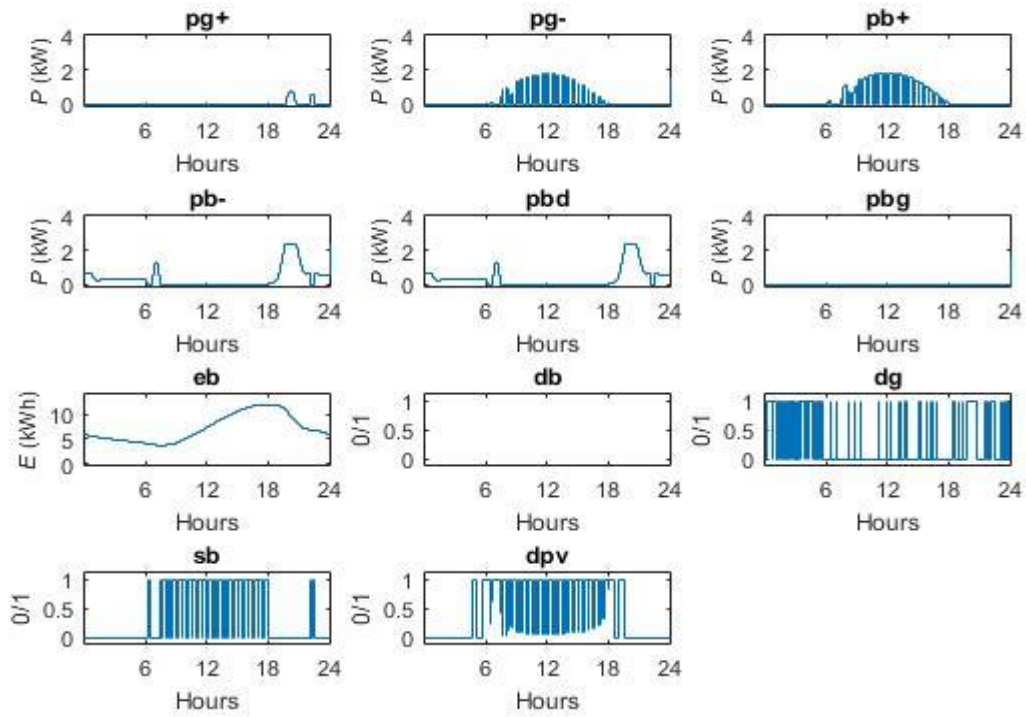


Fig. 7.2.1.1. Decision factor curves on 1<sup>st</sup> January, 2013

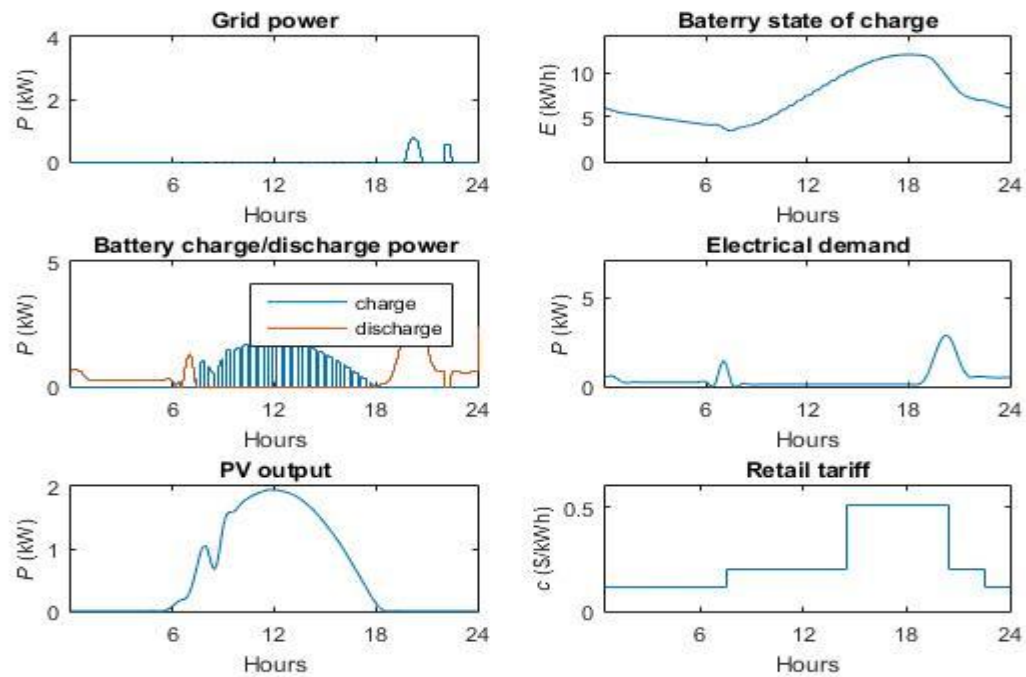


Fig. 7.2.1.2 Separate curves on 1<sup>st</sup> January, 2013

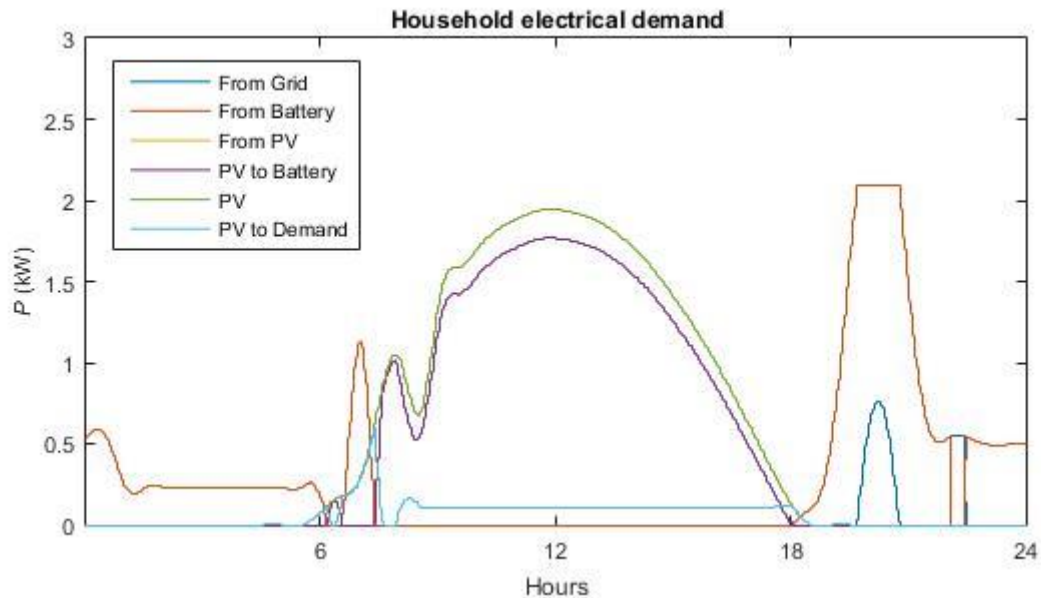
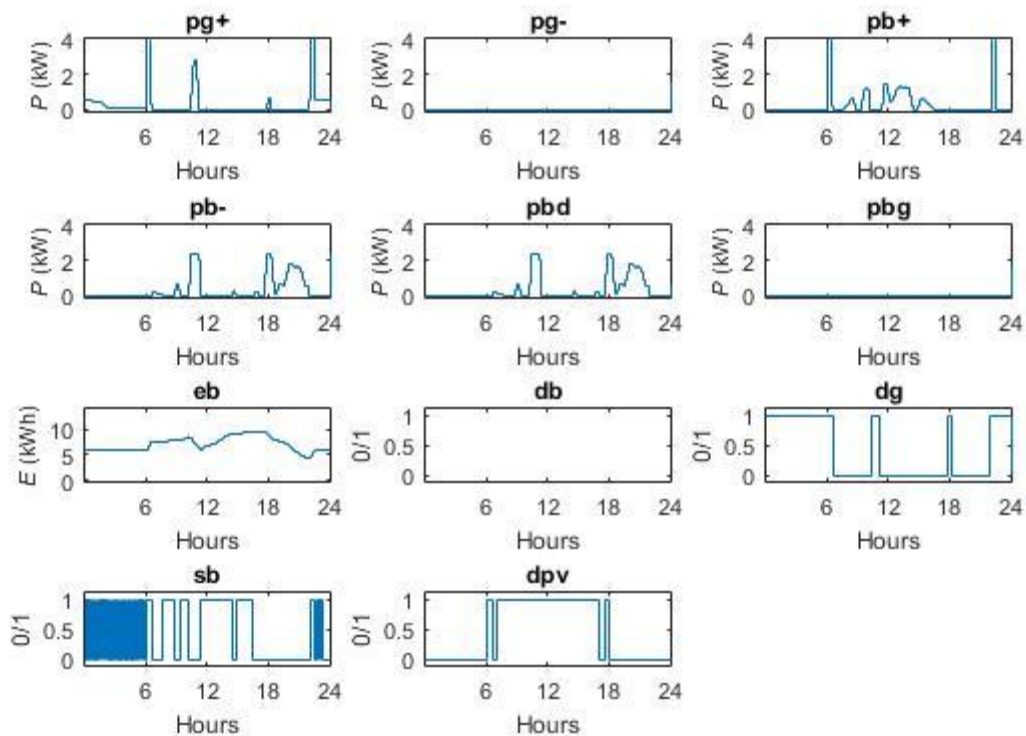


Fig. 7.2.1.3 Combined curves on 1<sup>st</sup> January, 2013

## 7.2.2 Result on 14th July, 2013— winter weekend

The resultant plot of a typical winter weekend is shown and analyzed below:



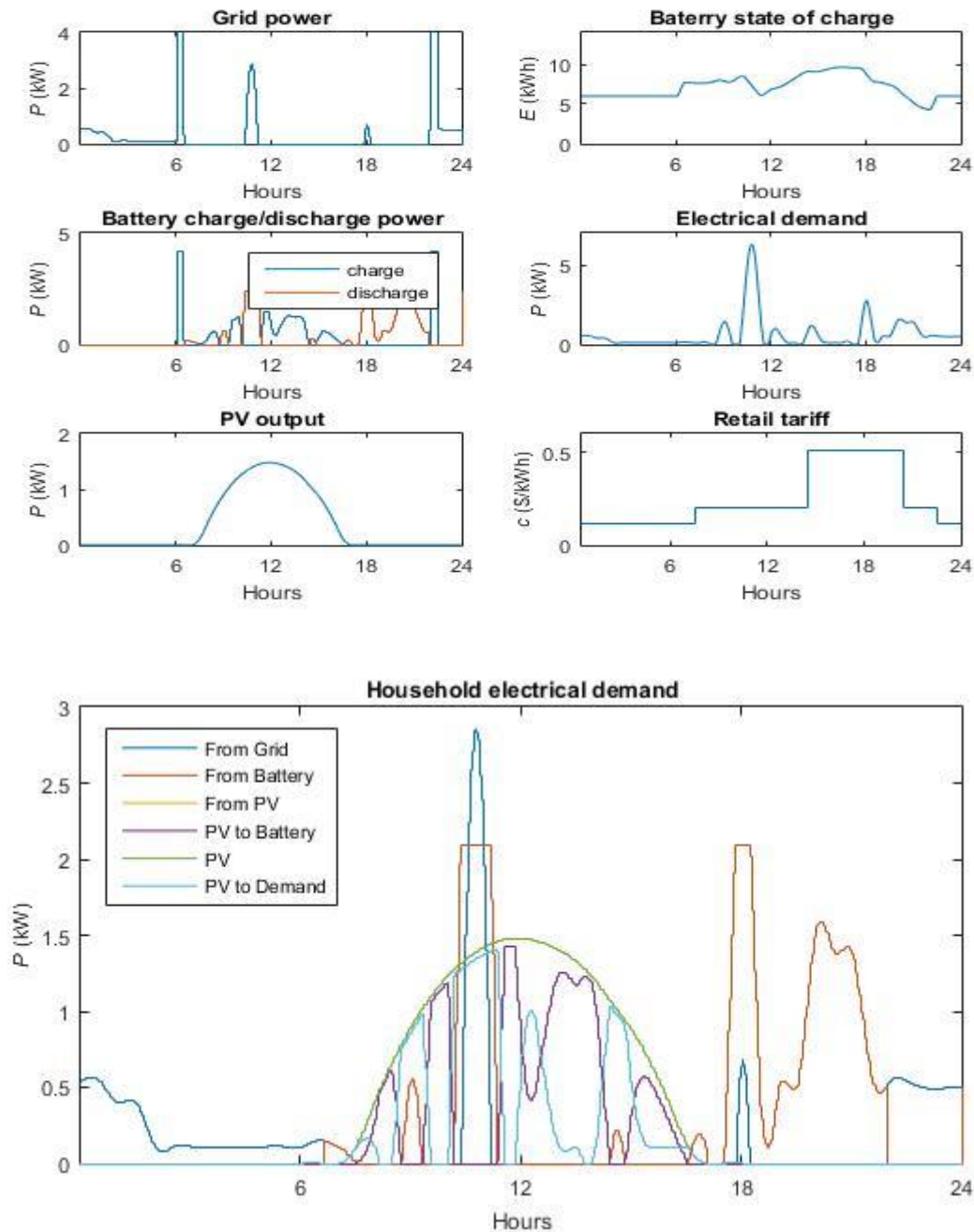


Fig. 7.2.2.1 Resultant plots of a typical winter weekend

Compared with the weekdays, it is obvious that consumption during the day is much higher. The portion of the PV output supplying to the demand is larger. The battery need to extract electricity from the grid in the morning in order to supply the demand of the day. Since the power demand at each point of the day varies significantly, the battery needs to charge and discharge at various rate instead of a consistent rate, which can potentially harm the lifespan of the battery. (The figures for all 4 different cases can be accessed in [Project\\_Group11\\_final/EMS figures](#))

## 8 Determine the economic viability of the project by means of a cash-flow analysis

This section aims to analyse the economic viability of the proposed PV-battery system above through analysing the payback period and Net Present Value after 20 years.

### 8.1 Factors related to this project

To calculate the cash flow, the following factors need to be considered:

- Initial investment,  $\Delta P$

Sum of the cost (including the installation fees) of the PV panels, inverter and the battery.

- Annual savings,  $\Delta A$

Yearly saving compared to the original electricity cost.

- The present value of future money

$$P = \frac{F}{(1+d)^n}$$

where  $F$  is the amount of the future money,

$d$  is the discount rate,

$n$  is the number of years of investment.

- The present value of a stream of annual cash flows,  $P$

$P = A \cdot PVF(d, n)$ , where  $PVF = \frac{(1+d)^n - 1}{d(1+d)^n}$ .

$$PVF = \frac{1}{1+d} + \frac{1}{(1+d)^2} + \dots + \frac{1}{(1+d)^{n-1}} + \frac{1}{(1+d)^n} = \frac{(1+d)^n - 1}{d(1+d)^n}$$

- Discount rate,  $d$

This PV-battery system could last for a period of more than 20 years, so the discount rate of the money needs to be considered into the calculation.

According to [18], the discount rate in Australia published in 28<sup>th</sup> February 2013 by the Australia Central bank is 3%.

- Escalation rate,  $e$

The price of the electricity increases every year, therefore, the escalation factor of the electricity price has to be considered.

According to [19], the escalation rate of the Australian residential electricity is 5%.

- Investment duration,  $n$

$n$  is the length of this PV-battery system, in this case, it is 20 years according to the life length of the PV panels.

- Annual degradation,  $\lambda$

$\lambda$  is the degradation factor of the PV panel's efficiency that influence the output power. According to the specification data sheet, it is 0.7%.

## 8.2 Comparison of different installation choice

The use of different combinations of hardware are analysed here and this part helps to decide which case is the best one to choose.

Hardware key information:

- PV panels  
The information could be found in Section 6.
- Inverters  
The information could be found in Section 6.
- Batteries  
The information could be found in Section 6.
- Charge controllers  
The information could be found in Section 6.
- Trackers
  - Zomeworks UTRF 168 Universal Tracker  
Price: US \$3,262.00, i.e. AU \$4566.8

## 8.3 4 cases for installation consideration

4 combinations of the installation alternatives of the PV-battery system for the family are considered by analysing the cash flow.

The 4 cases being considered are:

- 12 PV panels (250W), 12 batteries, without trackers
- 10 PV panels (250W), 12 batteries, with trackers
- 12 PV panels (250W), 10 batteries, without tracker
- 14 PV panels (250W), 12 batteries, without trackers

### 8.3.1 Case 1: 12 PV panels (250W), 12 batteries, without trackers

Initial cost  $\Delta P = 12 \times \$314 + 12 \times \$322 + \$2240 + \$138.6 = \$10010.6$

By simulating the Matlab code for the cash flow, the annual savings of Case 1 is determined to be \$918.09.

According to the specifications in Section 6.2, the life cycle of the PV panel, inverter and batteries are 25 years, 20 years and 10 years respectively. To calculate the cash flow for a duration of 20 years, it is required to replace the battery again in the 10<sup>th</sup> year, that is  $P_{\text{battery}} = \frac{12 \times 322}{(1+0.03)^{10}} = \$2875.18$ .

So the actual  $\Delta P$  is  $\$10010.6 + \$2875.18 = \$12885.78$ .

According to the data sheet of the PV panel, the supplier provides a warranty for 10 years which include the workmanship, so the maintenance fee will be paid from the 11<sup>th</sup> year.

According to [20], the overall annual inspection fee for the rooftop solar system is about \$150, plus the average cost of \$18 per panel for cleaning the PV panels.

So, the maintenance fee for the period from 11<sup>th</sup> to 20<sup>th</sup> year is:

$\$150 + 12 \times \$18 = \$366$  per year.

With the electricity escalation factor  $e$  and the degradation factor  $\lambda$ , to calculate the equivalent discount rate  $d'$ .

$$\frac{(1+e)(1-\lambda)}{1+d} = \frac{1}{1+d'}$$

$$\Downarrow$$

$$d' = \frac{1+d}{(1+e)(1-\lambda)} - 1$$

The equivalent discount rate is

$$d' = \frac{1+d}{(1+e)(1-\lambda)} - 1 = \frac{1+0.03}{(1+0.05)(1-0.0007)} - 1 = -0.01836047138$$

$$PVF(d', n) = \frac{(1+d')^n - 1}{d'(1+d')^n}$$

To calculate the Net Present Value,

$$NPV = \Delta A \times PVF(d', 10) + \Delta A' \times \sum (P_{11} \text{ to } P_{20}) - \Delta P = \$918.09 \times 10.70099544 + (\$918.09 - \$366) \times \left\{ \frac{1}{(1+d')^{11}} + \frac{1}{(1+d')^{12}} + \frac{1}{(1+d')^{13}} + \frac{1}{(1+d')^{14}} + \frac{1}{(1+d')^{15}} + \frac{1}{(1+d')^{16}} + \frac{1}{(1+d')^{17}} + \frac{1}{(1+d')^{18}} + \frac{1}{(1+d')^{19}} + \frac{1}{(1+d')^{20}} \right\} - \$12885.78 = \$3613.7$$

Similarly, the Net Present Value of the other 3 cases are calculated to be \$289.08, \$4441.9, \$3615.3 respectively

## 8.4 Cash flow of the chosen cases

Case	1	2	3	4
PV Panels	12	10	12	14
Battery	12	12	10	12
Tracker	NA	With tracker	NA	NA
NPV	\$3613.7	\$289.08	\$4441.9	\$3615.3
Payback period	15	20	10,14	15

Table 8.4.1 Comparison of NPV between 4 cases

Fig. 8.4.1 shows the simple cash flow every single year, and Fig. 2 shows the cumulative cash flow.

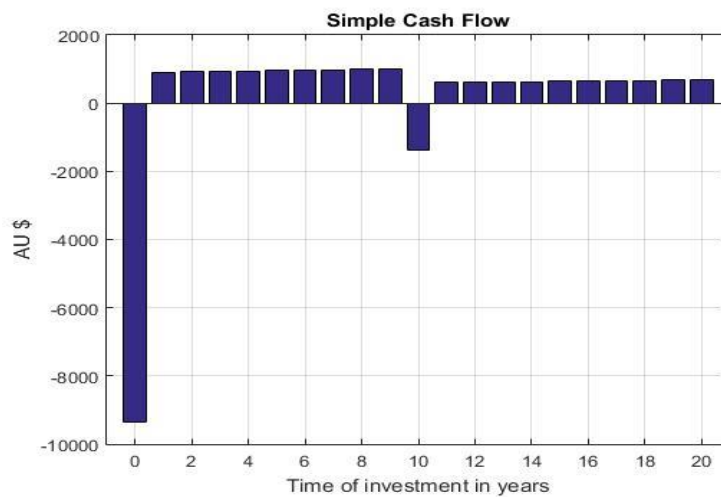


Fig. 8.4.1 Simple cash flow

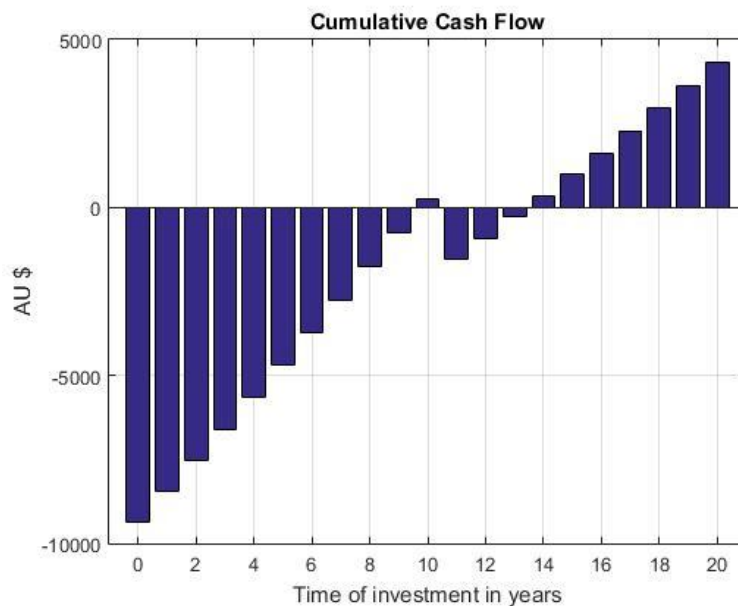


Fig. 8.4.2 Cumulative cash flow

Based on the Net Present Value calculation and simple and cumulative cash flow analysis it can be determined that out of the chosen cases, the optimal solution is to use 12 fixed angle PV panels with 10 unit 1.2kWh battery. The payback period is determined to be 10 years, however, due to the reinstallation of the PV panel system, only from year 14 the family starts to gain benefit consistently.

## 9 Conclusion

In conclusion, throughout the investigation on locations, solar resources, electricity demand, tariff structure, PV-battery system, energy management system and cash flow analysis, a proposal for installing a PV system is designed for a working young couple.

The system contains 12 pieces of mono-crystalline fixed angle PV solar panels, 10 1.2kWh AGM batteries, one inverter and one charge controller. The system is both physically and economic feasible. The payback period for the system is 14 years and under a 20 years duration analysis, a surplus earning of AU\$4441.9 can be expect at the end of the duration.

However, it is worth mentioning that the electricity demand of the household can increase greatly in the following years due to child support. The stability of the family needs to be taken into consideration. Home-moving may occur for potential reasons including career opportunities and environmental concerns. Also more factors need to be taken into consideration in the simulation result. It cannot reach a conclusion whether the household should invest on the PV system since the benefit and drawback are equally strong.

Throughout the project designing procedure, a better understanding of the reality of PV system is generated comprehensively. The team members coordinate through the project and the team generates a supporting atmosphere. Communication skills of the team members are improved which contributes to further research activities.

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## 11 Appendix

### 11.1 Cash flow calculation for other 3 cases

#### 11.1.1 Case 2: 10 PV panels (250W), 12 batteries, with trackers

Initial cost  $\Delta P = 10 \times \$314 + 12 \times \$322 + \$2170 + \$138.6 + \$4566.8 = \$13879.4$

By simulating the Matlab code for the cash flow, the annual savings of Case 2 is determined to be \$922.87.

To replace the battery again in the 10<sup>th</sup> year, the cost is  $P_{\text{battery}} = \frac{12 \times 322}{(1+0.03)^{10}} = \$2875.18$ .

So the actual  $\Delta P$  is  $\$13879.4 + \$2875.18 = \$16754.88$ .

The maintenance fee for the period from 11<sup>th</sup> to 20<sup>th</sup> year is:

$$\$150 + 10 \times \$18 = \$330 \text{ per year.}$$

To calculate the Net Present Value,

$$\begin{aligned} \text{NPV} = & \Delta A \times \text{PVF}(d', 10) + \Delta A' \times \sum (P_{11} \text{ to } P_{20}) - \Delta P = \$922.87 \times 10.70099544 + (\$922.87 - \$330) \times \left\{ \frac{1}{(1+d')^{11}} + \right. \\ & \left. \frac{1}{(1+d')^{12}} + \frac{1}{(1+d')^{13}} + \frac{1}{(1+d')^{14}} + \frac{1}{(1+d')^{15}} + \frac{1}{(1+d')^{16}} + \frac{1}{(1+d')^{17}} + \frac{1}{(1+d')^{18}} + \frac{1}{(1+d')^{19}} + \frac{1}{(1+d')^{20}} \right\} - \\ & \$16754.88 = \$289.08 \end{aligned}$$

#### 11.1.2 Case 3: 12 PV panels (250W), 10 batteries, without tracker

Initial cost  $\Delta P = 12 \times \$314 + 10 \times \$322 + \$2240 + \$138.6 = \$9366.6$

By simulating the Matlab code for the cash flow, the annual savings of Case 3 is determined to be \$905.14.

To replace the battery again in the 10<sup>th</sup> year, the cost is  $P_{\text{battery}} = \frac{10 \times 322}{(1+0.03)^{10}} = \$2395.98$ .

So the actual  $\Delta P$  is  $\$9366.6 + \$2395.98 = \$11762.58$ .

The maintenance fee for the period from 11<sup>th</sup> to 20<sup>th</sup> year is:

$$\$150 + 12 \times \$18 = \$366 \text{ per year.}$$

To calculate the Net Present Value,

$$\begin{aligned} \text{NPV} = & \Delta A \times \text{PVF}(d', 10) + \Delta A' \times \sum (P_{11} \text{ to } P_{20}) - \Delta P = \$905.14 \times 10.70099544 + (\$905.14 - \$366) \times \left\{ \frac{1}{(1+d')^{11}} + \right. \\ & \left. \frac{1}{(1+d')^{12}} + \frac{1}{(1+d')^{13}} + \frac{1}{(1+d')^{14}} + \frac{1}{(1+d')^{15}} + \frac{1}{(1+d')^{16}} + \frac{1}{(1+d')^{17}} + \frac{1}{(1+d')^{18}} + \frac{1}{(1+d')^{19}} + \frac{1}{(1+d')^{20}} \right\} - \\ & \$11762.58 = \$4441.9 \end{aligned}$$

### 11.1.3 Case 4: 14 PV panels (250W), 12 batteries, without trackers

Initial cost  $\Delta P = 14 \times \$314 + 12 \times \$322 + \$2450 + \$138.6 = \$10848.6$

By simulating the Matlab code for the cash flow, the annual savings of Case 1 is determined to be \$974.03.

To replace the battery again in the 10<sup>th</sup> year, that is  $P_{\text{battery}} = \frac{12 \times 322}{(1+0.03)^{10}} = \$2875.18$ .

So the actual  $\Delta P$  is  $\$10848.6 + \$2875.18 = \$13723.78$ .

The maintenance fee for the period from 11<sup>th</sup> to 20<sup>th</sup> year is:

$\$150 + 14 \times \$18 = \$402$  per year.

To calculate the Net Present Value,

$$\begin{aligned} \text{NPV} = & \Delta A \times \text{PVF}(d', 10) + \Delta A' \times \sum (P_{11} \text{ to } P_{20}) - \Delta P = \$974.03 \times 10.70099544 + (\$974.03 - \$402) \times \left\{ \frac{1}{(1+d')^{11}} + \right. \\ & \left. \frac{1}{(1+d')^{12}} + \frac{1}{(1+d')^{13}} + \frac{1}{(1+d')^{14}} + \frac{1}{(1+d')^{15}} + \frac{1}{(1+d')^{16}} + \frac{1}{(1+d')^{17}} + \frac{1}{(1+d')^{18}} + \frac{1}{(1+d')^{19}} + \frac{1}{(1+d')^{20}} \right\} - \\ & \$13723.78 = \$3615.3 \end{aligned}$$

## 11.2 Electricity bills of the household

Meter no	Previous read	Current read	Usage (kWh)	Bill days
068125			120.118	86
			225.243	86
			335.956	86

(A = Actual, E=Estimated)

Charges:	Usage (kWh)	Charge	Amount
22 Apr 15 to 30 Jun 15 (70 Days)			
Peak Usage			
Energy Use	94.46	43.18 c/kWh	\$40.79
Off-Peak Usage			
Energy Use	180.415	9.93 c/kWh	\$17.92
Shoulder Usage			
Energy Use	257.327	19.68 c/kWh	\$50.64
Supply Charge		153.08 c/Day	\$107.16
01 Jul 15 to 16 Jul 15 (16 Days)			
Peak Usage			
Energy Use	25.658	43.35 c/kWh	\$11.12
Off-Peak Usage			
Energy Use	44.828	10.16 c/kWh	\$4.55
Shoulder Usage			
Energy Use	78.629	20.35 c/kWh	\$16.00
Supply Charge		161.65 c/Day	\$25.86
Total*			\$274.04

\*Peak periods apply from 2pm - 8pm on working weekdays. Shoulder periods apply from 7am - 2pm, 8pm - 10pm working weekdays and 7am - 10pm on weekends and public holidays. Off Peak periods apply all other times. Times displayed are Australian Eastern Standard Time, unless you have an interval meter, in which case day light savings will apply if relevant.

Fig.11.1.1 Electricity bills summary from 22<sup>nd</sup> April to 16<sup>th</sup> July, 2015

Meter no	Previous read	Current read	Usage (kWh)	Bill days
068125			114.815	92
			287.374	92
			417.513	92

(A = Actual, E=Estimated)

Charges:	Usage (kWh)	Charge	Amount
20 Jan 15 to 28 Feb 15 (40 Days)			
Peak Usage			
Energy Use	55.649	43.18 c/kWh	\$24.03
Off-Peak Usage			
Energy Use	151.503	9.93 c/kWh	\$15.04
Shoulder Usage			
Energy Use	198.043	19.68 c/kWh	\$38.97
01 Mar 15 to 21 Apr 15 (52 Days)			
Peak Usage			
Energy Use	59.166	43.18 c/kWh	\$25.55
Off-Peak Usage			
Energy Use	135.871	9.93 c/kWh	\$13.49
Shoulder Usage			
Energy Use	219.47	19.68 c/kWh	\$43.19
20 Jan 15 to 21 Apr 15 (92 Days)			
Supply Charge		153.08 c/Day	\$140.83
Total*			\$301.10

\*Peak periods apply from 2pm - 8pm on working weekdays. Shoulder periods apply from 7am - 2pm, 8pm - 10pm working weekdays and 7am - 10pm on weekends and public holidays. Off Peak periods apply all other times. Times displayed are Australian Eastern Standard Time, unless you have an interval meter, in which case day light savings will apply if relevant.

Fig.11.1.2 Electricity bills summary from 20<sup>th</sup> January to 21<sup>st</sup> April, 2015

## Electricity Usage and Service Calculation

Next Scheduled Read: 22 Apr 15 (+- 2 business days)      Last Meter Read: 22 Oct 14

Description:      Billing Period: 22 Oct 14 to 19 Jan 15

General Supply ToU      (90 Days) (A = Actual, E=Estimated)

Usage:

Meter No.	Current Reading	Previous Reading	Usage kWh	Total kWh	Bill Days
068125			119.335		90
			283.607		90
			394.094	797.036	90

Charges:	Usage kWh	Charge/Rate c/kWh	Amount \$
Peak Usage			
Energy Use	119.335	43.18	51.53
Off-Peak Usage			
Energy Use	283.607	9.93	28.16
Shoulder Usage			
Energy Use	394.094	19.68	77.56
Supply Charge			137.77
Sub-Total			295.02

Fig.11.1.3 Electricity bills summary from 22<sup>nd</sup> Oct, 2014 to 19<sup>th</sup> January, 2015

## Electricity Usage and Service Calculation

Next Scheduled Read: 21 Jan 15 (+- 2 business days)      Last Meter Read: 21 Jul 14

Description:      Billing Period: 21 Jul 14 to 21 Oct 14

General Supply ToU      (93 Days) (A = Actual, E=Estimated)

Usage:

Meter No.	Current Reading	Previous Reading	Usage kWh	Total kWh	Bill Days
068125			154.129		93
			266.02		93
			390.861	811.01	93
Charges:			Usage kWh	Charge/Rate c/kWh	Amount \$
21 Jul 14 to 14 Sep 14 (56 Days)					
Peak Usage					
Energy Use			95.165	45.52	43.32
Off-Peak Usage					
Energy Use			160.358	12.27	19.68
Shoulder Usage					
Energy Use			240.251	22.02	52.90
Supply Charge					85.72
15 Sep 14 to 21 Oct 14 (37 Days)					
Peak Usage					
Energy Use			58.964	43.18	25.46
Off-Peak Usage					
Energy Use			105.662	9.93	10.49
Shoulder Usage					
Energy Use			150.61	19.68	29.64
Supply Charge					56.64
Sub-Total					323.85

Fig.11.1.4 Electricity bills summary from 21<sup>st</sup> July to 21<sup>st</sup> October, 2014

### 11.3 Instantaneous PV-output for a week using 14 PV panels of fixed angle

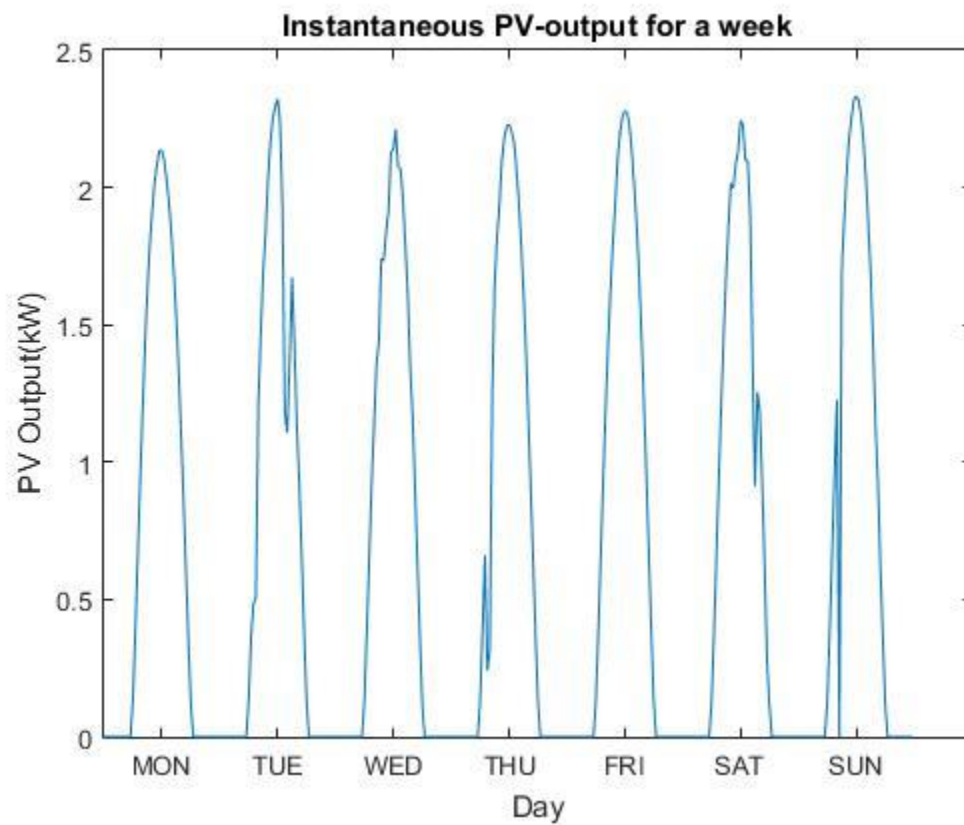


Fig.11.2.1 Instantaneous PV-output for a week using 14 PV panels of fixed angle

## 11.4 Summary of electricity demand

Seasonal total demand (weekday)							
Spring		Summer		Autumn		Winter	
Wh		Wh		Wh		Wh	
daylight	dark	daylight	dark	daylight	dark	daylight	dark
1170	3510	1152	3456	1152	3456	1152	3456
86710	53820	85376	55936	85376	52992	85376	52992
6500	6500	6400	6400	6400	6400	6400	6400
8612.5	17225	8480	16960	8480	16960	8480	16960
0	26000	0	25600	0	25600	0	25600
19500	19500	19200	19200	19200	19200	19200	19200
7800	39000	7680	38400	7680	38400	7680	38400
0	2925	0	2880	0	2880	0	2880
14300	42900	14080	42240	14080	42240	14080	42240
32500	0	0	0	0	0	64000	
0	0	32000	64000	0	0	0	0
0	26000	0	25600	0	25600	0	25600
0	2600	0	2560	0	2560	0	2560
0	0	6400	28800	6400	32000	0	0
1170	1170	1152	1152	1152	1152	1152	1152
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0
178262.5	241150	181920	333184	149920	269440	207520	237440
419412.5	(total)	515104	(total)	419360	(total)	444960	(total)

Fig.11.3.1 Seasonal total demand of weekdays

Seasonal total demand (weekend)							
Spring		Summer		Autumn		Winter	
Wh		Wh		Wh		Wh	
daylight	dark	daylight	dark	daylight	dark	daylight	dark
1404	1404	1404	1404	1404	1404	1404	1404
34684	21528	34684	21528	34684	21528	34684	21528
5200	2600	5200	2600	5200	2600	5200	2600
10335	6890	10335	6890	10335	6890	10335	6890
5200	10400	5200	10400	5200	10400	5200	10400
7800	7800	7800	7800	7800	7800	7800	7800
3120	15600	3120	15600	3120	15600	3120	15600
0	1170	0	1170	0	1170	0	1170
11440	17160	11440	17160	11440	17160	11440	17160
0	0	0	0	0	0	26000	0
0	0	52000	0	0	0	0	0
0	15600	0	15600	0	15600	0	15600
0	2080	0	2080	0	2080	0	2080
0	0	2600	13000	2600	13000	0	0
468	468	468	468	468	468	468	468
364	0	364	0	364	0	364	0
0	0	0	0	0	0	0	0
91000	0	91000	0	91000	0	91000	0
13000	0	13000	0	13000	0	13000	0
184015	102700	238615	115700	186615	115700	210015	102700
286715 (total)		354315 (total)		302315 (total)		312715 (total)	

Fig. 11.3.2 Seasonal total demand of weekends

Spring	Summer	Autumn	Winter
kWh	kWh	kWh	kWh
706.1275	869.419	721.675	757.675

Fig.11.3.3 Seasonal total demand

## 11.5 Simple and cumulative cash flow charts

### 11.5.1 Case 1—12 fixed angle PV panels with 12 batteries

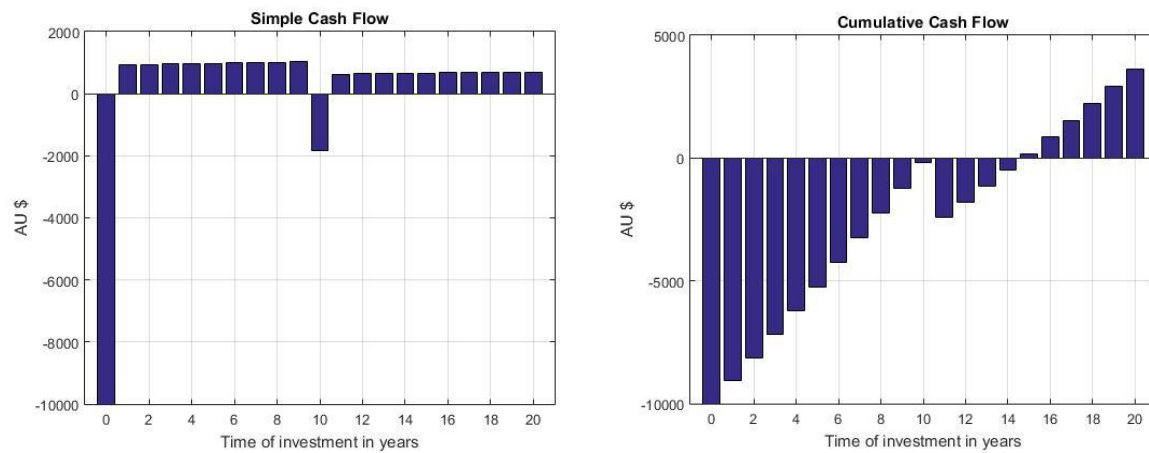


Fig.11.4.1.1 Simple and cumulative cash flow charts for Case 1—12 fixed angle PV panels with 12 batteries

### 11.5.2 Case 2—10 one axis tracking PV panels with 12 batteries

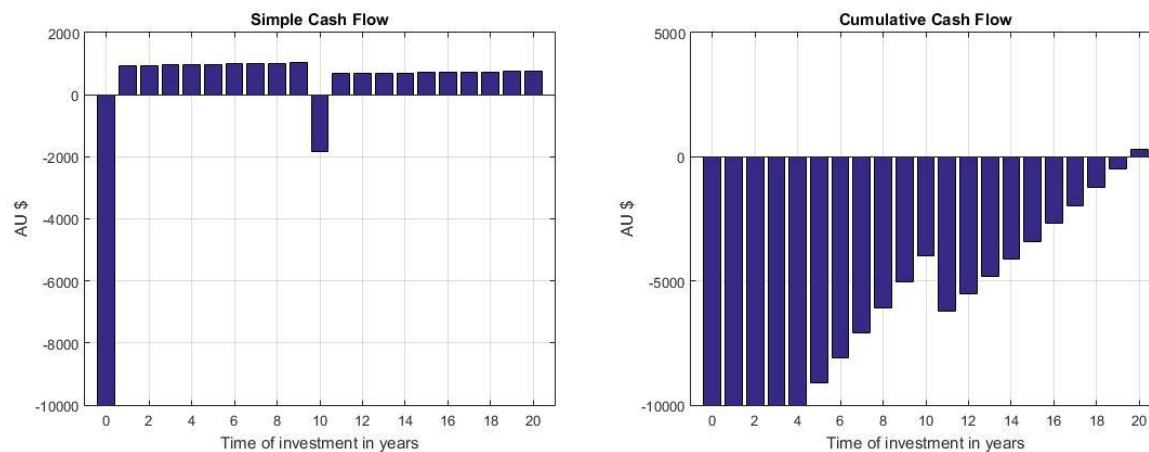


Fig.11.4.2.1 Simple and cumulative cash flow charts for Case 2—10 one axis tracking PV panels with 12 batteries

### 11.5.3 Case 4—14 fixed angle PV panels with 12 batteries

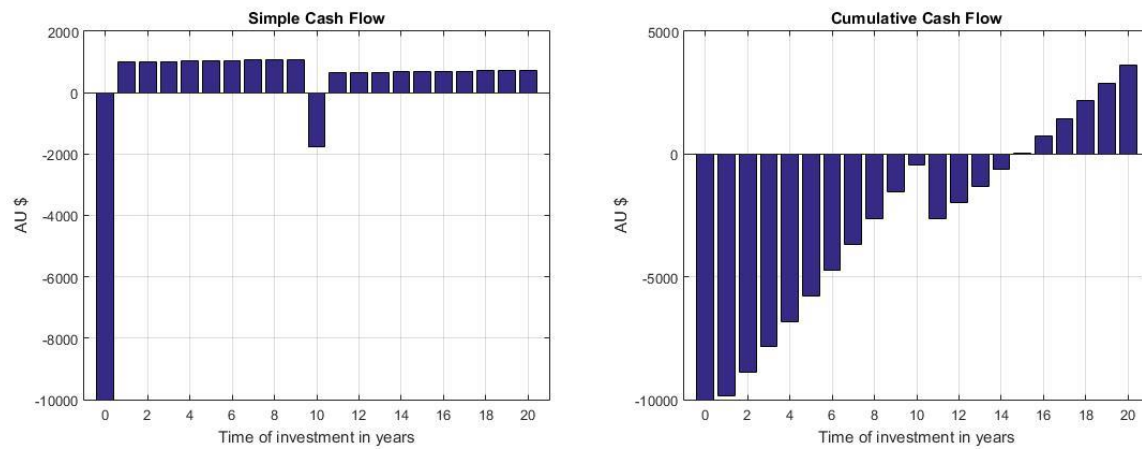


Fig.11.4.3.1 Simple and cumulative cash flow charts for Case 3—14 fixed angle PV panels with 12 batteries